Aalto University
School of Engineering

Aalto University
School of Engineering
Department of Mechanical Engineering

Janne Syvänen

# Evaluation and Development of the Over-run Test of Studded Tyres

Master's Thesis

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.

Espoo 27.7.2016

Thesis supervisor — Professor Kari Tammi

Thesis advisors — Mika Loponen, M.Sc. (Tech.)
Panu Sainio, Lic.Sc. (Tech.)

**Aalto University**
**School of Engineering**

Aalto University
P.O. BOX 11000, FI-00076 AALTO
www.aalto.fi

**Abstract of master's thesis**

**Author** Janne Syvänen

**Title of thesis** Evaluation and Development of the Over-run Test of Studded Tyres

**Degree programme** Mechanical Engineering

**Major** Machine Design **Code** K3001

**Thesis supervisor** Prof. Kari Tammi

**Thesis advisors** Mika Loponen, M.Sc. (Tech.); Panu Sainio, Lic.Sc. (Tech.)

**Date** 27.7.2016 **Number of pages** 97+9 **Language** English

## Abstract

Studded tyres are widely used in Finland and some other countries during winter. Primary reasons for their use are better performance in harsh conditions (on slippery ice) and the ability to even out the performance in varying winter conditions. However, the use of studded tyres is much argued, and the road wear caused by them brings on issues. Costs due to reconstruction or rehabilitation of pavement are an economical issue, whereas dust as worn material may cause respiratory diseases, for instance, and it is felt inconvenient especially in tightly populated city areas. The noise impact of studded tyres is also considered as negative.

For these reasons, the road wear effect of studded tyres is controlled and restricted. Traditionally, the properties of studs and tyres have been regulated, but currently the most common way to get an approval for a studded tyre is the over-run test. The test enables innovative technical solutions as it actually measures the road wear whereas the traditional approval practise was based on measuring dimensions. The over-run test in its current form, however, has been found to provide varying results depending on the tester and the testing conditions. The purpose of the thesis was to inspect numerical data about the over-run test trials, and detect factors causing systematic differences. The available test data was mainly provided by a working group formed by the testers – the task force – and no data was produced either in the framework of the thesis or by Finnish Transport Safety Agency (Trafi), the orderer of the thesis. The main method was statistical analysis, but also theoretical and qualitative reflection was used.

As a result of the study, uniform handling of the over-run and reference stones was assessed to be one possible improvement to decrease the variation of the results as moisture in a test piece (stone) may cause a significant part of the mass loss detected in the test. In addition, the setting of the stone samples on a track was concluded to be a reason for unequal wear values of consecutive stone rows in one test. The test method description was also discovered to allow variation in vehicle load, tyre pressure and tyre size, for example, that together may affect the road wear. A suggestion was also made to continue the research of different stone geometry to reduce the effect of random variation.

Based on the findings in the thesis, the task force agreed to study the presented factors and take the results of the thesis into account in their development project regarding the same issue. In addition, the suggestions for improvement were discussed with Trafi, and the intention is to consider them in the upcoming reform of the over-run test method description. No official changes will be made before the presumptions have been proved by comparison tests. The final evaluation of the proposed improvements will, therefore, be made after the upcoming test rounds.

**Key words** over-run test, winter tyre, studded tyre, road wear, type-approval, tyre testing

**Aalto University**
**School of Engineering**

**Aalto-yliopisto**
**PL 11000, 00076 AALTO**
**www.aalto.fi**

**Diplomityön tiivistelmä**

| | |
|---|---|
| **Tekijä** Janne Syvänen | |
| **Työn nimi** Nastarenkaiden yliajokokeen arviointi ja kehittäminen | |
| **Koulutusohjelma** Konetekniikka | |
| **Pääaine** Koneensuunnittelu | **Koodi** K3001 |
| **Työn valvoja** Prof. Kari Tammi | |
| **Työn ohjaajat** DI Mika Loponen; TkL Panu Sainio | |
| **Päivämäärä** 27.7.2016 **Sivumäärä** 97+9 | **Kieli** Englanti |

**Tiivistelmä**

Nastarenkaita käytetään laajalti Suomessa ja tietyillä muilla alueilla talven aikana. Tärkeimmät syyt nastarenkaiden käytölle ovat niiden hyvä pitokyky vaikeimmissa talviolosuhteissa (liukkaalla jäällä) ja niiden tasaiset ominaisuudet keliolosuhteiden vaihdellessa. Nastarenkaiden käyttö on kuitenkin herättänyt paljon keskustelua niiden aiheuttaman teiden kulumisen takia. Tiepäällysteen uusimistarve tuo mukanaan kustannuksia, kun taas tien kuluessa syntyvä pöly saattaa aiheuttaa hengitystieongelmia ja vähintään tuntua epämiellyttävältä erityisesti kaupunkiympäristössä. Myös nastarenkaiden aiheuttama melu koetaan paikoin haitalliseksi.

Edellä mainituista syistä nastarenkaiden tienkuluttavuutta on pyritty hallitsemaan. Perinteisesti nastojen mittoja ja niiden asettelua renkaalle on rajoitettu, mutta nykyään suurimmalle osalle nastarenkaista haetaan tyyppihyväksyntä yliajokokeen kautta. Yliajokokeessa mitataan tienkuluttavuutta pelkkien nastan mittojen ja asettelun sijaan, ja se mahdollistaakin uuden ja innovatiivisen nastarengasteknologian kehittämisen. Yliajokokeen tuloksissa on kuitenkin havaittu testaajista ja testiolosuhteista riippuvia eroja. Diplomityön tarkoituksena oli tarkastella numeerista testaustietoa yliajokokeesta ja tunnistaa erityisesti tekijöitä, jotka aiheuttavat systemaattisia virheitä. Yliajokokeen kehittämistä varten perustettu työryhmä tarjosi pääosin kaiken tässä työssä käytetyn testausdatan, eikä dataa tuotettu työn puitteissa eikä työn tilaajan, Liikenteen turvallisuusviraston (Trafi), toimesta. Tärkein menetelmä diplomityössä oli tilastollinen analyysi, mutta ilmiöitä tarkasteltiin myös teoreettisesti.

Diplomityön tuloksena arvioitiin, että yliajokoe- ja referenssikivien yhtenäinen käsittely vähentäisi testitulosten vaihtelua, sillä kosteus koekappaleissa (kiveä) voi muodostaa suuren osan massamuutoksesta, jota testissä mitataan. Lisäksi koekivien asettelu niille tarkoitettuun kehykseen pääteltiin aiheuttaneen peräkkäisten kivirivien systemaattiset erot kulumassa. Yliajokokeen menetelmäkuvauksen todettiin myös mahdollistavan vaihtelun testiajoneuvon kuormassa, rengaspaineessa ja rengaskoossa, mikä saattaa vaikuttaa testitulokseen. Ehdotuksena esitettiin myös, että erilaisia koekiven geometrioita tulisi tarkastella laajemmin jatkossa, jotta voitaisiin pienentää satunnaisvirheiden merkitystä.

Diplomityön analyysin ja tulosten pohjalta yliajokokeen kehitystyöryhmä jatkaa tutkimusta esiin tuotujen muuttujien ja tekijöiden parissa. Tehdyt ehdotukset yliajokokeen kehittämiseksi otetaan huomioon myös Trafissa, kun yliajokoemenetelmä päivitetään. Muutoksia ja tarkennuksia ei kuitenkaan tule tehdä, ennen kuin niiden vaikutukset on tutkittu tulevien testauskierrosten aikana.

**Avainsanat** yliajokoe, talvirengas, nastarengas, tienkuluminen, tyyppihyväksyntä, rengastestaus

## Acknowledgement

*The thesis was conducted by the order of Finnish Transport Safety Agency (Trafi), and my sincerest acknowledgement and thanks are addressed to Marko Sinerkari who provided the subject and enabled the funding for this research. The thesis advisor Mika Loponen also deserves a huge thank for all the guidance and support along the project. I also much appreciate all the other people at Trafi for instructive conversations and co-operation. The thesis supervisor professor Kari Tammi provided guidance and valuable advice on scientific writing and thesis project. Special thanks also go to the other thesis advisor, Panu Sainio, for extensive technical knowledge and valuable guidance during the project. The thesis would not have been possible without the open and kind attitude of the working group of the over-run test that provided the vital reference data and shared their experiences. I am also grateful for all the other people met and involved in discussions.*

*Very special thanks go to my mom for essential guidance on writing and to my dad for technical ideas. Support during my studies has also been great! Finally, I would like to express my gratitude to my beloved fiancée Eeva who has supported me during this journey!*

Helsinki 27.7.2016

Janne Syvänen

# Table of contents

# Table of symbols

| | | |
|---|---|---|
| $A$ | [m$^2$] | footprint area of a tyre |
| $G$ | [N] | gravitational force |
| $I$ | [kgm/s] | momentum of a stud when hitting a road |
| $c_{ref}$ | | relational change in a mass of a reference stone sample during a test |
| $g$ | [m/s$^2$] | gravitational coefficient |
| $l$ | [m] | length of a footprint of a tyre |
| $m$ | [kg] | mass for an inspected tyre |
| $m_{stud}$ | [kg] | mass of a stud |
| $r$ | [m] | nominal radius of a tyre |
| $r_{dyn}$ | [m] | dynamic rolling radius of a tyre |
| $w$ | [m] | width of a footprint of a tyre |
| $T_1$ | [K] | temperature at the beginning of a test |
| $T_2$ | [K] | temperature during a test |
| $m_{cor}$ | [kg] | reference corrected mass of a test sample after over-runs |
| $m_{start}$ | [kg] | mass of a test sample before over-runs |
| $m_{end}$ | [kg] | mass of a test sample after over-runs |
| $m_{r\_start}$ | [kg] | mass of a reference stone sample before over-runs |
| $m_{r\_end}$ | [kg] | mass of a reference stone sample after over-runs |
| $p_1$ | [Pa] | gauge pressure of a tyre at a temperature $T_1$ |
| $p_2$ | [Pa] | gauge pressure of a tyre at a temperature $T_2$ |
| $p'_1$ | [Pa] | absolute pressure of a tyre at a temperature $T_1$ |
| $p'_2$ | [Pa] | absolute pressure of a tyre at a temperature $T_2$ |
| $p_{nor}$ | [Pa] | normal atmospheric pressure |
| $v_r$ | [m/s$^2$] | radial velocity of a stud in relation to a vehicle’s coordinate system |
| $v_{rel}$ | [m/s] | velocity of a stud in relation to tyre tread surface |
| $v_{stud}$ | [m/s] | velocity of a stud in relation to a vehicle’s coordinate system |
| $v_t$ | [m/s$^2$] | velocity of a stud at a track contact in relation to a vehicle’s coordinate system |
| $v_{track}$ | [m/s] | velocity of a track in relation to a vehicle’s coordinate system |
| $v_{veh}$ | [m/s] | velocity of a vehicle |
| $\alpha$ | [rad] | angle of incidence of a stud toward road surface |
| $\Delta E_k$ | [J] | change in a kinetic energy of a stud when hitting a road |
| $\Delta m_{final}$ | [kg] | reference corrected mass loss of a test sample |
| $\Delta m_{mea}$ | [kg] | mass loss of a test sample without a reference correction |
| $\Delta m_{ref}$ | [kg] | change in a mass of a reference stone sample during a test |
| $\Delta v$ | [m/s] | difference of velocities of a track and stud |
| $\Delta v_{stud}$ | [m/s$^2$] | change in a velocity of a stud when hitting a road |
| $\omega$ | [rad/s] | angular velocity of a wheel |

# Abreviations

| | |
|---|---|
| ATCF | The Automobile and Touring Club of Finland |
| ESC | Electronic stability control |
| ETRMA | The European Tyre & Rubber Manufacturers' Association |
| FMI | The Finnish Meteorological Institute |
| FTA | Finnish Transport Agency |
| FWD | Front wheel drive |
| KIT | Karlsruhe Institute of Technology |
| RWD | Rear wheel drive |
| Trafi | Finnish Transport Safety Agency |
| VTI | The Swedish National Road and Transport Research Institute |
| VTT | Technical Research Centre of Finland Ltd |
| 2WD | Two wheel drive |
| 4WD | Four wheel drive |

# 1 Introduction

## 1.1 Background

Winter tyres are considered reasonable in Finland and a few other countries during the winter season. The Finnish law requires their use, whereas in Sweden and Norway, for instance, they are optional. Studded winter tyres have been a much discussed topic in Finland ever since tyre manufacturers started to offer them some 50 years ago. People quickly adopted them and their popularity increased. Today, studless winter tyres – so called Nordic friction tyres – have established themselves in the market beside traditional studded tyres. However, around 80% of the winter tyres used in Finland are still studded (Unhola, 2015). On the other hand, the use of studded tyres in cities in Japan and Norway, for example, is forbidden due to their harmful effects.

The positive and negative effects of studded tyres have been evaluated by numerous parties for decades (e.g. Zubeck, et al., 2004; Elvik, et al., 2013). As one obvious favourable effect, studded tyres increase the friction between the tyre and an icy road especially at warmer temperatures (Rantonen, et al., 2012). Studded tyres also even out the performance in varying conditions on a road. Thus, accidents due to difficult winter conditions may reduce. Nevertheless, studs also have many negative sides: the main concerns are costs due to the need of reconstruction or rehabilitation of pavement and particle emissions (dust) as a result of pavement wear. Emissions especially in densely populated city areas may cause health issues. In addition, the noise emitted by studded tyres has been considered harmful. For these reasons, the use of studded tyres in these intensively operated road networks in some cities is either limited or forbidden. Hence, ensuring good characteristics on ice while reducing road wear sets one of the main challenges for the winter tyre industry.

The first legislation on studded tyres in Finland was introduced in the 1970s when studded tyres began to be common and some disadvantages were found. Since those days, the main objective has been to control the road wear. At that time, laws were enacted to limit the mass of a stud and the number of them on a tyre. Nowadays, those same factors are regulated in addition to the protrusion of a stud and the stud force, for instance. Before 2003, it was not possible to launch studded tyres on the market if these limit values – physical properties of a tyre or a stud – were not met. Since then, manufacturers have been able to bring a studded tyre to the market if it can be proved that it does not wear the pavement more than tyres meeting the earlier mentioned limit values (Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003). Later, in 2010, the over-run test method has been taken into use to indicate the level of road wear caused by a particular tyre with particular studs.

During the past few years when the over-run test has been used and its position in the type-approval procedures has been studied, it has been noticed that relatively large errors in the results between test laboratories may occur with the test method. It has been noticed that the method in its current form may give incomparable results in different laboratories. The test results can differ depending on the tester, but on the other hand, the repeatability within one operator seems to stay in limits – therefore, if all tests were conducted by the same laboratory, the comparability of the results would improve. However, all the interest groups would need the method to be improved so that it can justifiably be a part of the approval procedure not only in Finland, but also in other countries.

## 1.2 Objectives

The main objective on the large scale is to improve the over-run test: it should be sufficiently reliable and transferable as a part of the type-approval procedures. This thesis presents the situation today, the history of the over-run test and the legislative environment. Companies that perform over-run tests – recognised experts – together with Finnish Transport Safety Agency (Trafi) have been developing the over-run test procedure based on the same issues. The thesis belongs to this development process.

The recognised experts have carried out experiments in co-operation and thus, produced test data on the variables of the over-run test. One main objective of this thesis is to analyse the data and recognise the effects of different variables. The aim is to find variation between several factors, and, based on the analysis, some concrete improvements for the over-run test method are presented. By these improvements systematic errors should be eliminated, and the transferability of the test should increase. In addition, factors that cannot be eliminated and facts that cannot be found due to limited data are presented and the need for further study is expressed. The research questions are the following:

- Can the factors that cause systematic errors on the over-run test be recognised based on the available test data, and how could the error be eliminated?
- Is the random error significant in the test and can it be reduced?
- Can the over-run test be made reliable and transferable enough only by improving the test method description?
- What other improvements for the over-run test or road wear test in general could be considered?

The society generally pursues to control and reduce road wear, and studded tyres play a significant role in this issue. Hence, it is crucial to have a reliable test method for road wear. Based on that, authorities can set reliable and predictable limits for the road wear of studded tyres. Now that the results of today's test method cannot reliably be compared, the limit values and their lowering may not be seen as justified. On the other hand, testing laboratories may also be in unequal situations if the result of one operator differs from the others'. The objective is, in particular, to develop the over-run test method and to analyse the variables related to the test. Some concrete improvements to limit both systematic and random error in the test method are to be considered.

## 1.3 Methods

The first part of the thesis is based on literature survey. The background of the over-run test and the test method itself are presented. In addition, the mechanism and effects of the pavement wear related to studded tyres are discussed. For these, there are several Finnish and international studies and reports. As a conclusion for this section, it is explained how the over-run test has become a significant part of the type-approval procedure of studded tyres in Finland.

The main objective of the thesis is to develop the over-run test by the improvements based on the analysis of the test data produced by the recognised experts. Therefore, the statistical analysis composes a significant part of the thesis, and it has a major role as the most important method relative to the objectives of the paper. In addition to the statistical analysis, also a theoretical analysis and calculations have been utilised to support and complete the other results.

There is an opportunity to co-operate with the authorities, testing companies (recognised experts), manufacturers of studs and tyres and other experts in this field. That is why interviews and consultation are important parts of methods and reference material. They have decades of experience of studded tyres and the over-run test. Interviews provide also an excellent chance to explore different attitudes and considerations within all parties.

## *1.4 Definitions*

The study explores the physical phenomena of the pavement wear and the primary factors of studded tyres and the environment affecting that especially in the over-run test and not necessarily on real roads. The reflection between the over-run test and road wear in real driving conditions is not widely analysed. In addition, no considerable attention has been paid to the consequences of the usage of studded tyres, such as health or noise issues. The paper only discusses the existing over-run test and no other test methods are widely considered. The objective is not to find all the facts, variables, phenomena and improvements, and a need for further study is stated at the end.

The thesis evaluates the over-run test as a significant part in the type-approval procedures. Limit values for road wear in such procedures need to be defined justifiably, and the development of the limits needs to be foreseeable. This is significant concerning both the manufacturers and the society. However, the thesis does not discuss about the limit values for road wear in the over-run test. The procedure to define the limits is considerable as such, and only the principle of the limits is mentioned whenever it is inevitable. Another matter that is related to the limit values – the changing process if the over-run test would be much changed and thus, the limit values should be changed – is not widely considered, but it has been taken into account when evaluating the suggestions for development.

The numerical test data and the analysis of it compose a major part of the thesis, and many of the results of this paper are based on the findings from the data. What needs to noticed, any of the numerical test data has been produced in the framework of the thesis, and all the data has already been existing when the thesis work has begun. Moreover, the orderer of the thesis, Finnish Transport Safety Agency (Trafi), has not produced the most recent data for its own purposes, so they are third parties, the testing companies, who have produced and provided most of the numerical test data utilised in this thesis.

# 2 Context and environment

## 2.1 *Involved parties*

### 2.1.1 Finnish Transport Safety Agency (Trafi)

The thesis relates to an ongoing analysis and development process in which the aim is to find systematic errors and their sources in the over-run test procedure. Improvements on the test are considered during the two-year project ending by the end of 2016. Later on, the description of the test procedure is to be updated. Finnish Transport Safety Agency (Trafi) as an authority has set a task force to perform the development process.

Trafi is the administrative and safety authority in charge of transport system regulatory in Finland. Its mission is to ensure safety and environmentally friendly transportation system in all areas of transport in Finland. Sustainable development of transportation also belongs to Tarfi's policies. The operations of Trafi are regulated in Finnish legislation (Act on the Finnish Transport Safety Agency 863/2009). Enacting laws in Finland is up to the Ministry of Transport and Communication and the Finnish Parliament: Trafi is only authorised to decide on lower level regulations but also has the responsibility to prepare and give comments on afoot acts. (Trafi, 2016)

Among other things, Trafi is responsible for the type-approval of vehicle components including tyres. The over-run test method for testing road wear of studded tyres is approved by Trafi. Trafi has created frames for the testing: the test method description and limits for testing conditions and, as a result of the test, threshold values for road wear itself. However, the over-run test is not created by Trafi.

As noted earlier, Trafi has set the task force to improve the over-run test, and especially to find factors that may cause systematic errors within the test method. The main responsibility for proposal for improvements lies with the recognised experts and Trafi only directs and controls the project. However, this thesis is a contribution to this development process on the behalf of Trafi.

### 2.1.2 Recognised experts

Recognised experts carry out tests, measurements and inspections and provide reports based on these concerning compliance in national type-approval, individual approval or small series type-approval (Trafi, 2016). These activities are legislated and inspected. With regard to the testing of studded tyres there are five companies which are allowed to carry out the over-run test and they together form the task force. The companies are:

- BD Testing Ltd.
- Goodyear Innovation Center Luxemburg
- Nokian Tyres PLC, Testing Laboratory
- Test World Ltd. and
- Tikka Spikes Ltd.

On a general level, the group pursues similar objectives that have been defined in this paper: to recognise and eliminate sources of systematic errors in the over-run test method, and thus, improve reproducibility and transferability of the test. However, tasks and targets are agreed so that overlapping activities can be avoided. Nevertheless, the same types of analysis are also to be done to figure out if the conclusions of people from different backgrounds are equivalent. The project will be finished at the end of 2016. Therefore, the timing of this thesis is convenient as a contribution to the project.

The objective of the paper is to analyse the data from field tests concerning factors and variables in the over-run test method. The recognised experts named earlier have produced all the test data on which the analysis in this thesis is based. In addition to quantitative material, the recognised experts also provide other information and share their knowledge and experiences concerning the test. The co-operation of Trafi and the recognised experts has been intense since the over-run test has been approved for type-approval procedures. During the thesis the same open dialogue continued.

### 2.1.3 Manufacturers of studs and tyres

As a third important party, which is affected by this thesis, are the manufacturers of studs and tyres. Normally it is one company which designs and manufactures studs and another which designs and manufactures tyres and assembles studs onto them. A final product, a studded tyre, is a result of this co-operation. The legislation and the type-approval procedures have an important influence over both manufacturers due to the direct connection to their products. No studded tyre can get into the market without a type-approval. Hence, they need to follow the legislation and procedures tightly. On the other hand, an authority cannot change procedures or methods too quickly or unpredictably, and thus, the communication between all parties needs to be maintained and development work should be done in co-operation, whenever possible.

In addition to the national situation, Finnish legislation has a significant role regarding the worldwide market of studded tyres. Type-approvals granted in Finland are recognised in Sweden while Norwegians partly follow them. This expands the influence area of the Finnish type-approval procedures. The Nordic countries together compose a reasonably large market for studded tyres so the market under the Finnish legislation is regarded as significant globally. The majority of potential manufacturers follow these regulations and the method to measure road wear. One also needs to keep in mind that everyone would benefit from harmonised legislation in all countries where studded tyres are widely used. Thus, the situation in Finland cannot be the only basis for improvements on the over-run test, and the matter needs to be considered on a wider, international level.

## *2.2 Effects of the use of studded tyres*

In some countries studded tyres are widely used so that the total percentage of kilometres driven with them in the road network has become significant. Different countries and their governments have taken divergent stands on the matter which is reflected in the level of the use of studded tyres among people. In Finland, people have for long favoured studded tyres and the percentage of their use is one of the highest in the world. However, the benefits on studless winter tyres have recently been increasingly pointed out. It needs to kept in mind that studless winter tyres here and later on in this paper refer to the so called Nordic winter tyres designed for icy and snowy conditions, not the winter tyres designed typically for wet or tough conditions in the winter in Middle Europe, for example. Nevertheless, the main arguments for studless winter tyres have been both the savings on cost of pavement damage and especially the health benefits resulting from reduction of particle emissions from road. Particle emissions are seen as a dust problem mostly in spring in cities with busy road networks. In addition, for the user the noise from studded tyres may be considered unpleasant which is considered as an advantage for studless winter tyres, too.

The use of studded tyres is legislated in all countries where they are widely used. More information on legislation in different countries is presented in chapter 2.3. Finland has traditionally had favourable attitude towards studded tyres ever since they came on the market. Figure 1 shows the evolution of the use of studded tyres in Finland and the snow statistics during the same period. One can easily see that the percentage of vehicle with studded tyres is significant during wintertime. The maximum percentage was reached in the early 1990s when around 96% of passenger cars were equipped with studded tyres during winter. Since then, the level has decreased but the situation has been stabilised to around 80%. This high usage level means that around one third of all kilometres driven (passenger cars and vans) in Finnish roads are driven with studded tyres (Unhola, 2015).

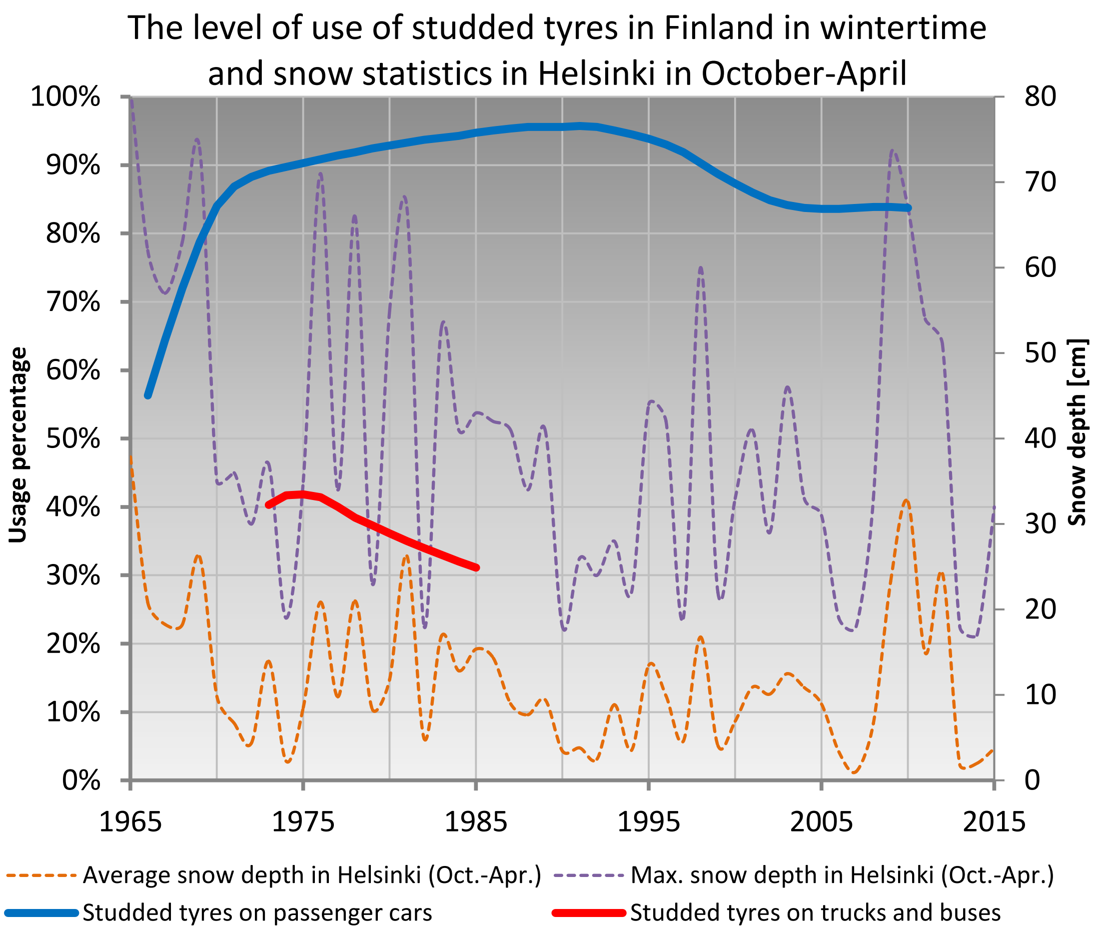



**Figure 1. Studded tyres have been common in Finland on passenger cars whereas their use on heavy vehicles has become negligible already decades ago (Unhola, 2015). The average amount of snow in Helsinki has been slightly decreasing at the same time but the variation is still large (FMI, 2016).**

Snow curves in Figure 1 represent an annual character of a winter. Even though the trends of both maximum snow depth and average snow depth are slightly descending, historically harsh winters have also been experienced during the past decade. In addition to variation between consecutive years, the character of winter may also differ radically during one season as can be noticed in Figure 2. For people choosing whether to use studded or studless winter tyres, such divergence cause a challenge.

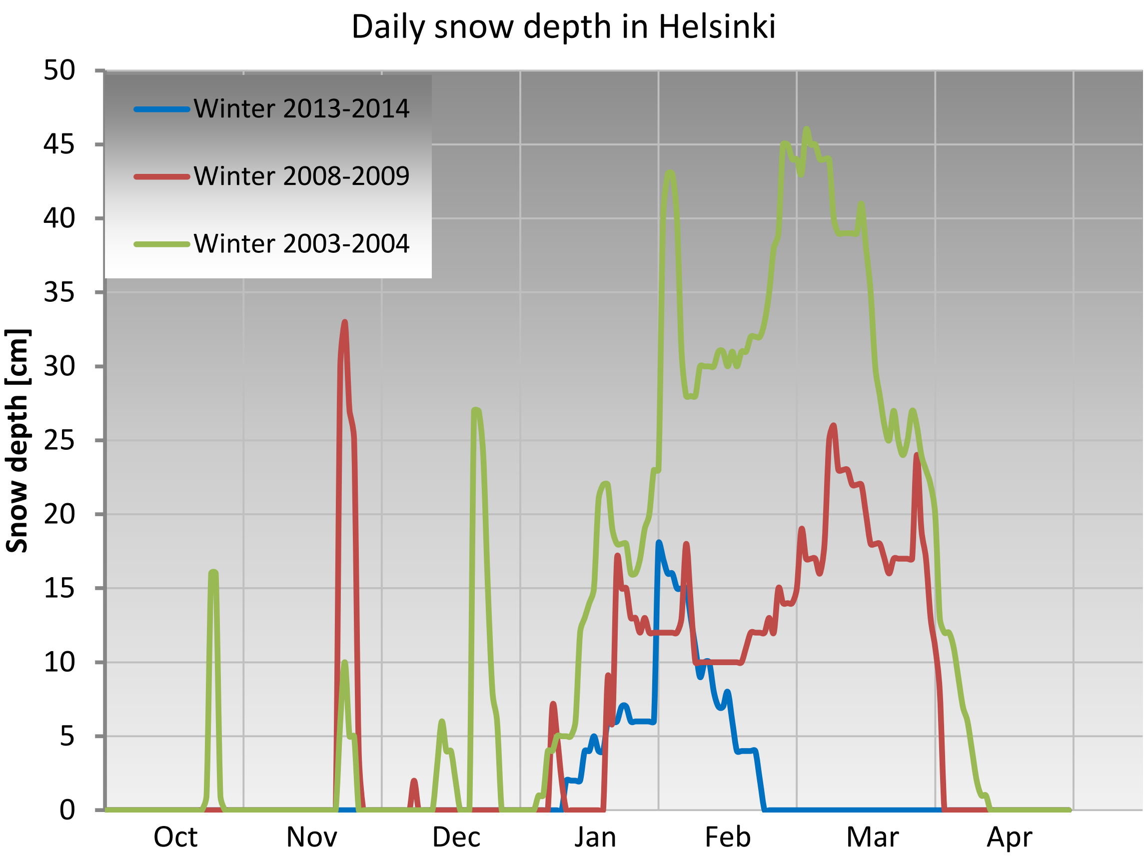



**Figure 2. Snow depth (in Helsinki) varies a lot depending a day and a year. (FMI, 2016)**

**Economic impact**

One of the main concerns regarding the use of studded tyres derives from the costs due to pavement wear and thus, due to pavement renewing. A need for the reconstruction or rehabilitation is usually arisen because of rutting: the tyres of each vehicle roll on the same line causing grooves to develop. This, in turn, means that the handling of vehicles becomes more challenging and the danger of hydroplaning increases, for instance. These phenomena may increase the danger of accidents and drivers feel them uncomfortable. Pavement renewing due to wearing depends mainly on the use of studded tyres and studless ones have hardly any effect on that. The rutting cause pavements to be renewed sooner but it does not increase the total wear. In addition to normal asphalt pavement, studded tyres wear off road markings, and concrete as a less durable pavement material in parking lots for example, is more sensitive to the damaging effect of studded tyres (Repo, 2006).

In addition to pavement wear, a need for reconstruction is caused by cultivation of pavement and ground material. The rutting is also caused by this phenomenon. Cultivation is composed of three different mechanisms:

- lateral creep on pavement
- densification of pavement
- densification and deformation of a base or subgrade (White, et al., 2002 p. 5).

In addition to these, Lampinen (1993, pp. 80–81) has added that so called early rutting that occurs due to mistakes during a construction phase may be significant. Cultivation does not depend on the type of the tyre and it exists through all seasons, mainly in warm seasons, though. What is more important, the number of heavy vehicles affects the rutting through cultivation. The rutting – as a result of either wearing or cultivation – occurs at most on stretches of road where strong accelerations, decelerations or turnings happen, and where lanes are narrower (Zubeck, et al., 2004 p. 102).

Besides primary costs due to the pavement renewing, some secondary costs also exist. With regard to health issues caused by dust, a more serious concern is obviously people's health itself. Anyway, dust or air pollution may cause financial costs due to increased use of health services and absences from work (Lanki, 2013 pp. 4–5). Studded tyres were banned in Japan in 1990s, when serious problem caused by road dust became evident. This issue related more to general convenience and experience of health due to inadequate research at that time, but after gradual prohibitions, the problem disappeared in a few years (Finnish National Road Administration, 1993 pp. 32–33). On the other hand, in areas, such as Alaska, with less operated road networks, no significant effects to health costs due to studded tyres have been found: hence, it is important to detect the differences between areas with various traffic volumes and transport systems when considering the effects of studded tyres (Zubeck, et al., 2004 pp. 134–136).

When considering whether studded tyres should be replaced by studless winter tyres, some additional cost on road maintenance need to be taken into account. Usually, this is thought to mean additional supply of abrasive material to increase friction (so called traction sand), chemicals to keep roads out of ice (so called salt) and snow ploughing. In the capital of Finland, Helsinki, the annual cost of sanding and salting in winter season is more than 1 million euros (City of Helsinki, 2013 pp. 24–25). In addition to all access and ring roads, several streets belong to the winter maintenance class *Is*, which means that roads are kept clean from ice and snow throughout the year apart from extreme conditions (City of Helsinki, 2016). Inspecting the whole road network in Finland, 42% of traffic is within this highest class (FTA, 2016). It may be considered if more streets and roads should belong to this highest class if studless tyres' share in winter traffic increased.

It is estimated that the maintenance budget would increase by a few hundred thousand euros in Helsinki if the role of studless tyres increased in the traffic in winter (City of Helsinki, 2013 pp. 24–25). However, this estimate includes some fundamental changes on methods of maintenance that are about to keep costs under a tighter control. Nevertheless, it may take a long time before studless tyres have a significant role in Helsinki, because additional sanding, salting and/or other means are not estimated to be necessary before the usage level of studded tyres decreases below 50%. Studies estimating the critical level of the use of studded tyres in urban areas indicate that a roughening effect of studded tyres on road surface become too low if less than half of tyres are studded, and thus, the surface become dangerously slippery (Malmivuo, et al., 2016 pp. 36, 44; Tuononen, et al., 2013 p. 12). It is the roughening effect that has been evaluated to have a more important safety effect than studded tyres primarily on one's car. More details on this are presented later on page 19 (Safety impact).

Regarding maintenance costs, a need for removal and/or binding of dust and abrasive material must also be taken into account. The impact of this is emphasised with increasing use of studless tyres. On the other hand, the use of studded tyres increases the amount of dust, too, through pavement wear, and thus, increases the need of its processing. It is difficult to define which of the cases would be the most cost-efficient based on the literature. However, dust is bound into snow and ice during winter, and the problems caused by dust are usually short-term in spring and they exist in all cases anyway. However, by ploughing, gathering and transporting snow outside a town during winter, the dust problems in spring can be reduced. Hence, smart maintenance could both help with the dust issue and improve cost-efficiency.

**Health impact**

During the recent years, health issues due to the use of studded tyres have been raised to be the primary argument in the conversation against studded tyres (City of Helsinki, 2013). Studded tyres clearly cause damage to pavement, and thus, produce particles of dust. More importantly, driving itself causes resuspension, which means dust on the road to rise in the air. Resuspended road dust is studied to be harmful for human beings in addition to inconvenience such as dry eyes or a cough. Particulate matter (PM) in size of $PM_{2.5}$ (diameter of a particle <2.5µm) and $PM_{10}$ (diameter of a particle <10µm, so called coarse particles) can cause respiratory deceases, for instance, and thus, increase morbidity and mortality (Chen, et al., 2011; Halonen, et al., 2009; Kim, et al., 2015). The major share of the dust from pavement is in size of $PM_{10}$ and only small portion of it belongs to $PM_{2.5}$ that is thought to be more harmful and thus, that is more studied out of these (Lanki, 2013 p. 11). Particles are also formed in larger sizes than coarse particles, but they cannot get into critical parts of human system – nonetheless, such dust is still felt uncomfortable.

It is notable that studded tyres themselves do not produce all of the road dust. First, there are many types of sources of dust in a city environment other than that from road wearing. Examples of these are vehicles' exhaust emissions and dust from wearing components of vehicles (tyres, clutch and brakes). Second, many sources which are not part of traffic produce different kinds of dust: construction sites as an example. Third, all the dust from the road wear is not caused by studded tyres: abrasive material (e.g. sand) applied to increase friction itself includes dust and in addition, it is also crushed into small particles under tyres. Moreover, abrasive material increases the wear of pavement due to "the sandpaper effect" (Kupiainen, et al., 2003; Gertler, et al., 2005). The sandpaper effect means that the abrasive material between a tyre and a road wears pavement. Also road salt has a similar effect on increased wear (Gertler, et al., 2005).

40–50% of resuspended road dust has been estimated to consist of worn pavement material, 25% of it consist of traction sand material and the rest comes from other sources (Kupiainen, et al., 2013 p. 13). The dust from pavement is considered to exist nearly only because of studded tyres. On the other hand, Tervahattu et al. (2002 p. 177) has studied a composition of road dust in experimental conditions and they have concluded that even

50% of the resuspended road dust is there due to the use of traction sand. It is notable that the share of dust from traction sand itself may be small, but it has a greater influence through the sandpaper effect (Kupiainen, et al., 2004). Hence, an increase in road dust is significant also with studless tyres if applying traction sand compared to not applying that. However, there are several controversial studies about this issue: Gustafsson et al. (2008b) has concluded that studded tyres give a 60–100 times higher particle concentration on sanded road surface in similar conditions than studless tyres which seems not to support the theory of the earlier mentioned sandpaper effect. However, differences on conditions may have occurred as the type of sand, material of pavement and external conditions have been deviating. It is road wear that is primarily studied in this thesis, but according to the study the particulate concentration and road wear in general correlate with each other (Gustafsson, et al., 2015b pp. 25–26). In addition, European Tyre and Rubber Manufacturers' Association (ETRMA) has recently conducted a comparison test study and concluded that the amount of particulate matter also correlates with the road wear in the over-run test (ETRMA, 2016). Thus, it seems reasonable to discuss about PM concentration – that is more widely studied – when evaluating factors affecting road wear, too.

**Noise impact**

In cities, traffic noise composes a major part of all noise emitted. The noise from vehicles derives basically from three different sources: tyre noise, aerodynamic noise and noise from a power source. The dominance of each source varies depending on a speed but most of the noise normally comes from the tyre-road contact at the speed range from 15–35km/h to at least highway speeds (Sandberg, et al., 2002 pp. 46–52). Kelkka et al. (2003 p. 15) estimates the speed range to settle between 40–120km/h. Nevertheless, the noise from a power source can get louder when accelerating. Anyway, it can be concluded that the properties of both a tyre and pavement are significant when considering the total noise level.

Large aggregate size in asphalt used in Finland and other corresponding countries makes pavement rougher when bitumen is quickly worn from the surface. This emphasises the tyre-road contact noise. Thus, so called silent pavement materials that attempt to maintain the smoothness of the surface, have been developed. This can be reached by applying a smaller aggregate size. These silent pavement materials have been studied for example in HILJA-research project (Kelkka, et al., 2003). Durability and economics were evaluated, too. Based on the project, the limit for silent pavement was set to 3dB(A) decrease compared to reference pavement at a speed of 50–60km/h. Although silent pavement materials are normally considered weaker on durability, a few materials were found to meet the requirements both on noise and durability. However, silent pavement materials are not widely in use because of costs and durability issues when using studded tyres.

Tyre-road contact noise when driving with studded tyres has been studied to increase 3–10dB(A) compared to that with studless tyres. This can be considered a significant increase in the total noise level. In addition to the tyre and pavement, the type of vehicle and especially the speed of vehicle affect the level. Studded tyres mostly produce noise when studs impact a pavement. With lower speeds, one can hear the noise from individual studs, but the sound from them is perceived as continuous when the speed rises above some 50km/h. (Lahti, 2003 pp. 18–20; Sandberg, et al., 2002 p. 242)

Exposure to noise can lead to loss of hearing only when the noise exceeds a level of 85–90dB(A) (Stansfeld , et al., 2003). On higher levels, the damage to hearing is faster. However, traffic noise can hardly ever reach this high intensity, and the harm from traffic noise may appear as non-auditory effects. For example, in Helsinki around 40% of citizens expose themselves to higher average noise level than the directive harm level 55dB(A) (Määttä, et al., 2012 p. 31). This high level of traffic noise may cause disturbances in sleep and concentration, stress and some mental or psychological disorders, depending on the type and level of the noise and the time exposed to it (Stansfeld , et al., 2003). To be clear, it needs to be mentioned that noise issues caused by studded tyres are usually thought to be minor compared to costs and health issues.

**Safety impact**

People use studded tyres because for safety reasons or as they feel that they are safe. The primary safety effect of studded tyres is limited to better friction on icy road in temperatures close to 0°C (Rantonen, et al., 2012). The extreme condition is met on wet ice when the friction coefficient is as low as some 0.1. Nordström (2004 p. 23) has concluded that the braking distance with studless winter tyres can be twice as long as that with studded tyres in such conditions. This reference cannot straight be applied to the today's situation as both types of tyres have been developed a lot. However, even more important for studded tyres is to even out friction properties in different conditions: it is safer to have moderate traction in all conditions than excellent traction on asphalt and poor on ice.

Elvik, et al. (1999, 2013) have concluded a positive effect on safety when using studded tyres. However, Elvik, et al. (2013) have noted that studded tyres have a bigger impact on external safety as they prevent pavement from polishing. On the other hand, according to the study based on statistics on crashes in Sweden, also a primary positive safety effect on cars with studded tyres has been found, especially regarding fatal crashes (Strandroth, et al., 2012). Junghard (1992) and Roine (1999 pp. 128–129) have concluded studded tyres to reduce the risk of accident, too. It must be noticed that these studies are old: both vehicle technology (for example anti-lock braking system and electronic stability control) and tyre technology (development on studless winter tyres and regulations to limit aggressiveness of studded tyres) have developed a lot since those days. Earlier mentioned studies conducted by Elvik, et al. must also be inspected critically as the data used has been partly produced in the 1990s.

Malmivuo (2012) has conducted a broad research on the safety effects of the decreasing use of studded tyres in Finland. Several studies related to the issues have been analysed: both those based on accident statistics, and those where physical properties, such as braking distances, have been examined. He has concluded that studded tyres provide undeniable improvement on ice and it is plausible that they are generally better in other conditions, too (Malmivuo, 2012 p. 51). However, the accident risk is – on average – only few per cent less when using studded tyres compared to studless tyres. On the harshest conditions, the risk is some 10% lower (Malmivuo, 2012 p. 53). These results may be regarded as current, although vehicle technology has an ever increasing role in traffic safety.

Concerning vehicle technology, one major improvement has been the electronic stability control (ESC). Elvik (2015) has stated that using vehicles with ESC, disadvantages of studless winter tyres can be avoided in most conditions. He also presents that ESC sets almost a perfect substitute for studded tyres and the introduction of ESC has weakened the safety argument of studded tyres.

Studded tyres have both primary and secondary safety effects. When considering traffic safety on a general level – not taking individuals into account– an interesting question is the share of studded tyres in traffic. They have a roughening effect on road surface preventing it from polishing unlike studless tyres. Tuononen and Sainio (2013, 2014) have studied the optimal proportion of studded tyres to keep the road rough enough. According to them a 25–50 percentage of studded tyres is required to keep the friction on surface sufficiently even compared to the situation in which all tyres are studded. Malmivuo et al. (2016 p. 36) have come to a similar conclusion saying that a 50 percentage of studded tyres is the critical limit. From the ECS point of view, it has been argued that a percentage of only 15 would be enough if all vehicle had that safety system (Elvik, 2015). Still under certain circumstances – on ice near 0°C – studded tyres are again a superior choice compared to studless ones: the laws of physics are something not to revoke (Scheibe, 2002 p. 18). However, it is important to consider how often one must drive under these conditions. If a car is not a necessity in daily life and one can adapt the driving style to the current conditions by proper speeds and anticipation, one manages as safely through the winter with studless tyres, too. It must be noted, though, that harsh and varying conditions may be common based on Figure 2 on page 15, and the tyres bought last for more than one season.

The comparison between studded and studless tyres is based not only on statistics and technical studies, but also on surveying psychological matters. Whereas studded tyres improve safety under certain conditions from a physical point of view, studless tyres may have an effect on drivers by making their driving style calmer and more careful. It has been estimated that the ban of use of studded tyres in Japan, and possibly instructions and education concerning studless tyres, had a reducing effect on accidents in conditions other than on ice near freezing point (Finnish National Road Administration, 1993 p. 31). Also Rumar et al. (1976) concluded that drivers with studded tyres drive faster than those with studless ones. However, this study is old considering just the development on studless tyres so the conclusion cannot be applied to the situation today. In a more recent study, it has been discovered that drivers with studded tyres drive slower (Elvik, et al., 2011). Also Mäkinen (1994, pp. 27–28) has reached a conclusion that drivers with studless tyres drive faster due to more comfortable and silent feeling in a car. This matter has surely many sides, and Scheibe et al. (2002 p. 52) have postulated three controversial points: (1) drivers with studded tyres drive safer because they generally care more about safety, (2) drivers with studded tyres drive faster due to a feeling of safety and (3) drivers with studless tyres do not drive in most difficult conditions. Based on these assumptions controversial conclusions can be made and studies based on statistics do not always tell the whole truth.

Because of the safety properties of studded tyres, they have been concluded to have more positive than negative effects in Finland (Unhola, 2004). Nevertheless, studied consequences of the use of studded tyres are limited as even here it is noticed that there is a great number of different kind of effects and ramification. It is always difficult to weigh the importance of human safety and economics. Therefore the use and bans of studded tyres are anything but simple and several countries have come to different conclusions as to whether studded tyres have more positive than negative sides. After all, the safety traffic is built from drivers' behaviour and attitude, and technology – whether it was about vehicles or tyres – just supports this.

## 2.3 Legislation

### 2.3.1 Current situation

The legislation concerning studded tyres can be divided into two parts: (1) regulations on the use of studded tyres and (2) regulations on the properties of tyres and studs. The legislation in Finland is presented in more detailed level – the over-run test method as an important part of it – whereas regulative environment in other countries is introduced shortly.

The use of winter tyres (studded or studless) is mandatory in Finland from the beginning of December to the end of February (Decree on the Use of Vehicles on the Road 1257/1992). This regulation concerns passenger cars, light-weight trucks and trailers with a mass of 0.75–3.5 tons. Additionally, some exceptions exist. Studded tyres are allowed to be used from the beginning of November to the end of March or to Monday week after Easter Monday. As noted earlier, around 80% of Finnish cars are equipped with studded tyres during a winter season (Unhola, 2015).

Studded tyres can be brought to the market through either of two different procedures. The traditional way is based on the properties of the studs and their setting on the tyre. These criteria are presented in Table 1. Additionally, some other properties of the stud are regulated, such as its shape. An approval is applied for a stud, and whenever approved studs are assembled onto a tyre according to the requirements, the tyre is eligible for the market without a separate approval. Studs can be assembled onto a tyre that is – according to the manufacturer – meant to be studded, and that has a general approval for tyres according ECE Regulation No. 30 by United Nations. (Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003)

**Table 1. The criteria for studs and their setting on a tyre according to the traditional method (Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003)**

| | | |
|---|---|---|
| *Number of studs per one circumference meter* | | *50* |
| *Max. protrusion of a stud [mm]* | Passenger car/ Light-weight truck | *1.2* |
| | Truck | *1.5* |
| *Max. stud force [N]* | Passenger car | *120* |
| | Light-weight truck | *180* |
| | Truck | *340* |
| *Max. mass of a stud [g]* | Passenger car | *1.1* |
| | Light-weight truck | *2.3* |
| | Truck | *3.0* |

In addition to the traditional method, a more recently introduced procedure requires an application for approval of a specific tyre-stud combination. In this procedure, it has to be proved that each type of tyre-stud combination does not wear pavement more than a reference studded tyre meeting the requirements of the traditional method (Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003). Since 2003, when the new method was taken into use, an approval was granted based on a reference test in which tyres were compared type by type. However, in 2010 Trafi introduced a harmonised way to test road wear: the over-run test. The test procedure is harmonised to reach reliable results (Trafi, 2014). In the over-run test, the weight loss of five similar test stones is measured after they have been driven over 200 times. This gives 400 roll-overs in total as the tyres in both axles roll over the stone samples. More details of the test method description are presented in chapter 2.3.2.

Finland and Sweden have co-operated closely concerning the legislation on studded tyres over the years. Sweden recognises type-approvals granted in Finland by Trafi (or corresponding authority before Trafi). Norway with slightly divergent attitude towards studded tyres has decided not to recognise approvals granted in Finland but they have granted approvals by exception rules to tyres that do not meet requirements similar to the traditional Finnish ones. The concern about the reliability of the over-run test has been bigger there.

No other pavement wear test is introduced worldwide – other than the Finnish over-run test – that would be included in the type-approval procedures. However, studded tyres are used in several areas worldwide and the concern on road wear and particle emissions increases all the time. Elsewhere only dimensions of studs and tyres are evaluated like in the traditional method in Finland (some exception rules may exist). Legislation in some countries where studded tyres have an important role in winter traffic is presented in Table 2. It would make sense to have common regulations in all these countries since the manufacturers could then offer the same tyres with the same approval in all parts of the world. Different legislation makes their lives difficult and does not support the best possible development towards low-wearing and high performance studded tyres. Decisions concerning taxes, bans or use periods belong to each country itself, but regulations for tyres should desirably be harmonised.

**Table 2. Legislation concerning studded and other winter tyres in some major countries (ATCF, 2016; Suokonautio-Hynninen, 2016; Savenius, 2002 pp. 60-81)**

| | ***Winter tyres: obligatory*** | ***Studded tyres: allowed*** | ***Regulations for a tyre/ additional information*** |
|---|---|---|---|
| ***Canada*** | *territory dependent* | *territory dependent* | • dimensions of a stud<br>• setting onto a tyre* |
| ***Finland*** | X | X | • *specific information above* |
| ***Japan*** | - | - | • studded tyres are only allowed on a road completely covered by snow or ice; otherwise their use is banned |
| ***Norway*** | - | (X) | • regulations concerning tyre properties are very similar to those in Finland<br>• exceptions for e.g. the number of studs on a tyre can be granted<br>• the use of studded tyres in large cities is controlled by taxes<br>• some bans in certain areas or streets are set |

| | | | |
|---|---|---|---|
| ***Russia*** | X | X | • dimensions of a stud<br>• setting onto a tyre* |
| ***Sweden*** | *situational* | X | • regulations concerning tyre properties are very similar to those in Finland<br>• tyres approved by the over-run test in Finland are recognised<br>• the use of winter tyres is obligatory only if weather conditions are tough during winter<br>• some bans in certain areas or streets are set |
| ***USA*** | *state dependent* | *state dependent* | • dimensions of a stud<br>• setting onto a tyre* |
| ***Other Europe*** | • Use of studded tyres in other countries in Europe is minor since snow or ice does not exist often<br>• The use is either restricted, banned or no stand on it has been taken<br>• The use of winter tyres can be obligatory in some countries, but so called light friction tyres (not “Nordic friction tyres”) are favoured<br>• Regulations for studded tyres follow general practise<br>• What is notable is that the use of snow chains is more often regulated | | |
| | **positions of the studs on the tyre tread, stud protrusion and stud force* | | |

## 2.3.2 The over-run test method

The over-run test has been under development since 1985 at VTT Technology Research Centre of Finland Ltd. The over-run test method has been improved little by little, but the basis has always remained the same. The main idea is to test the road wear of a real studded tyre in a real scale. However, the aim at the beginning has been to study the pavement wear and not tyres as such. Vehicle parameters can be determined freely and the conditions are controlled since a test is done within certain limits concerning weather, for instance. The wear value gotten as a result from the current over-run test defined by Trafi is:

> *“Over-run wear is the wear of five stone samples caused by 400 tyre roll-overs. The wear is determined by weighing the samples before and after the test, and it is expressed in grams. – – The driving speed of the vehicle in the test is 100 km/h for passenger vehicle tyres and 80 km/h for van and lorry tyres.”* (Trafi, 2013)

In addition, the course of the over-run test procedure in compact form is (Trafi, 2013):

(1) Selecting proper test stones i.e. samples (20 of them) by visual check (similar in dimensions, feasible on structure and shape)
(2) Cleaning the samples by dishwashing brush and compressed air
(3) Drying the samples at a temperature of 110°C for 72 hours
(4) Cooling the samples in a chamber with certain conditions (exsiccator, desiccator or similar) for 2 hours

(5) Weighing the samples under normal laboratory conditions: accuracy in measuring range at least 0.001g
(6) Packing the samples for a transport to a test site
(7) Installing the samples into a cleaned frame with rubber inserts between stones (can also be done already in a laboratory)
- Three consecutive rows of five samples
- Five samples to be reference stones

(8) Preparing the tyres (at least two weeks old and studded at least 48 hours before) for the test by a stud protrusion measurement and a stud force measurement
(9) Supplying water on the samples during the test to keep them constantly wet
(10) Driving over the samples 200 times at a speed of 100km/h (passenger vehicles) or 80km/h (other vehicles): driving both directions, accelerations and turnings are to be gentle (max. acceleration $2m/s^2$), atmospheric temperature 2–20°C
(11) Packing the samples for transport to a laboratory
(12) Repeating phases (2)…(5)
(13) The result is the average of the total wear of the stones in one row
(14) A. If the result is 10% below the limit value, the test is passed
B. If the result is less than 10% below the limit value, the test procedure is to be conducted again with new tyres and samples
i. If the result of the second test is below the limit value, the test is passed
ii. If the result of the second test is more than the limit value, the test is failed
C. If the result is more than the limit value, the test is failed
(15) Limit values for the over-run wear based on the tyre load rating classes are:
- 0.9g (<600kg)
- 1.1g (600–800kg)
- 1.4g (>800kg)
- 1.8g (C)

**History and description of the test**

Till the mid-1990s, multiple cylindrical test stones were used as samples, but due to their difficult handling and setting to a base, a new kind of test stone was developed. A right-angled stone sawed on top as a criss-cross was evaluated to be the most feasible for the test (see Figure 3). “Knobs” on the top surface represent the size of aggregate in real asphalt,

**Figure 3. The currently used test sample made out of Kuru Grey granite has dimensions of 90x75x20mm and it weights around 300g.**

and they enable greater wear through edge cleaving. There are 15 of these pieces of stones in three consecutive rows. Three rows are processed as separate specimens to include reliability examination in the test in a simple way. The test method description defines the maximum confidence interval for these three separate specimens. The final result of the test – the road wear value – is the average of the wear of each row. All 15 stone samples set into a frame on a test track are seen in Figure 4.

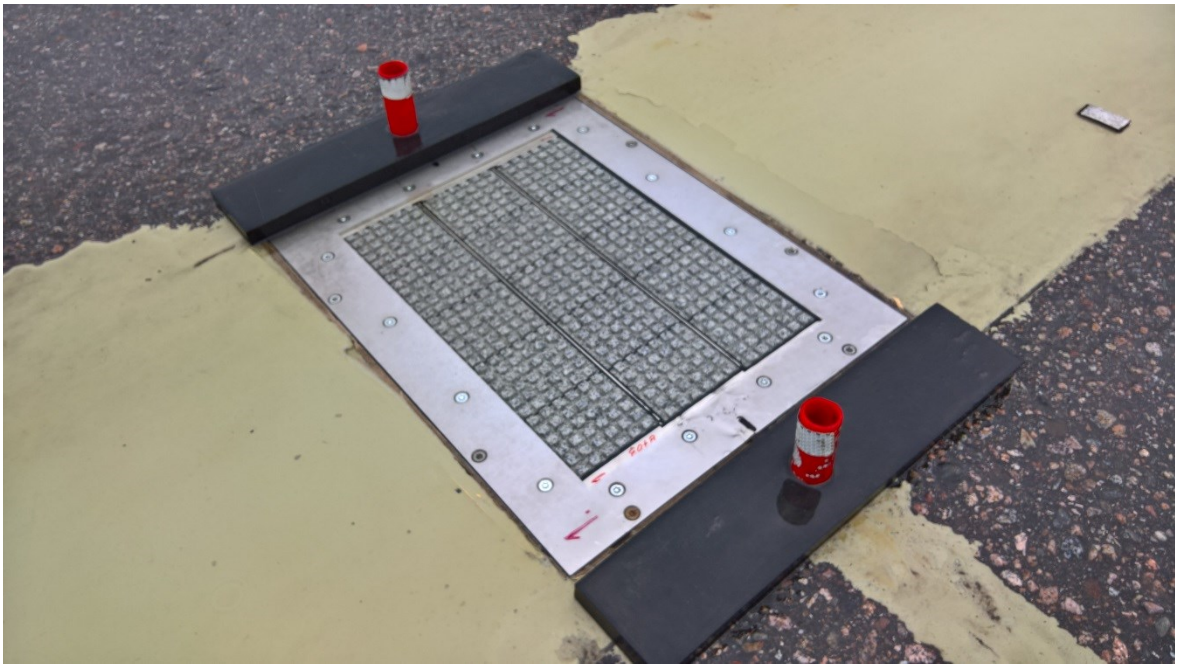


**Figure 4. Today, at most of the test sites/laboratories, the test samples are set in to the steel frame already in a laboratory, and the set is bolted in to certain spots on a test track. Three consecutive rows of five test stone samples result 15 test stones in total.**

The material of the test piece has been researched extensively especially during the research program of asphalt pavements (ASTO-project) in 1987–1992 when 12 different stone materials were under evaluation (Unhola, 2015). Kuru Grey granite has always been estimated to be the most feasible stone for the test due to its mineral composition, structure, grain size and grain orientation (Alkio, 2016). It is possibly the most homogeneous species of stone in Finland. In addition, the testers have now agreed that all the test samples come from the same excavation and stone manufacturer. Earlier one possible source of systematic error between testers occurred when they acquired stones from different suppliers. Other types of material have also been studied in the course of test's life, but nothing better has been found. The fundamental problem with metal test pieces generally is that only plastic deformation is occurred and no weight differences can be detected. Synthetic materials, such as mixes representing real asphalt, have also been evaluated, but the uniformity of material mass and especially the uncontrollability of the state of the material (moisture etc.) have been found as obstacles (Unhola, 2015).

The speed of a vehicle and the number of roll-overs have certainly an important effect on the success of the test. It has been stated that an increased number of roll-overs just increases the wear linearly so there is no need to put more effort on more over-runs, although it would statistically improve reliability (Unhola, 2015). However, also controversial opinions exist: Gültlinger (2014) says that the growth in wear is not linear due to a stronger edge cleaving at start. Anyway, 200 over-runs have been decided to give a sufficiently observable wear. The speed has been chosen to be the maximum generally allowed speed in Finland during wintertime to maximize the total wear (see the effect of vehicle speed in chapter 2.4.1).

The number of over-runs can be evaluated by calculating how many stud impacts actually produce the total wear in the test. It can likely be estimated that the major wearing mechanism in the test is the impact damage (see chapter 2.4.2). Considerable wear is detected on the edges of the knobs of the test sample, so in the calculation, it is estimated that effective impacts are those where the centre axis of a stud hits the area max 1mm from the edge of a knob to both directions (see Figure 5). Thus, the partial impacts due to a diameter of a pin have been taken into account. This causes mainly edge cleaving which has been identified as a major part of the wear (Unhola, et al., 2016). The calculation is continued with an assumption that studs are divided evenly per the circumference of a tyre. One normal size of 205/55R16 is evaluated over three different numbers of studs on a tyre. All these tyres are available in the market. The figures of the calculation are shown in Table 3.

The result – 0.36 as an effective knob ratio based on this calculation – means that some third of all studs on a tyre cause wear within the over-run test. Notably, the knob ratio is low, too, meaning that almost half of the studs hit nothing when rolling over. Still the wear in the test has been evaluated to be around ten times higher than in real driving conditions (Unhola, 2015). In a normal traffic environment on a smooth pavement, the "knob ratio" is presumably higher (most of the studs hit the road in every revolution), not to mention the case on pure concrete pavement with even a smoother surface. Thus, it seems clear that also from this aspect, the over-run test does not represent real driving conditions. On the other hand, that does not mean that the test would be unfeasible: wear in the test and in real conditions just occurs in a different way, but the results may be comparable, though.

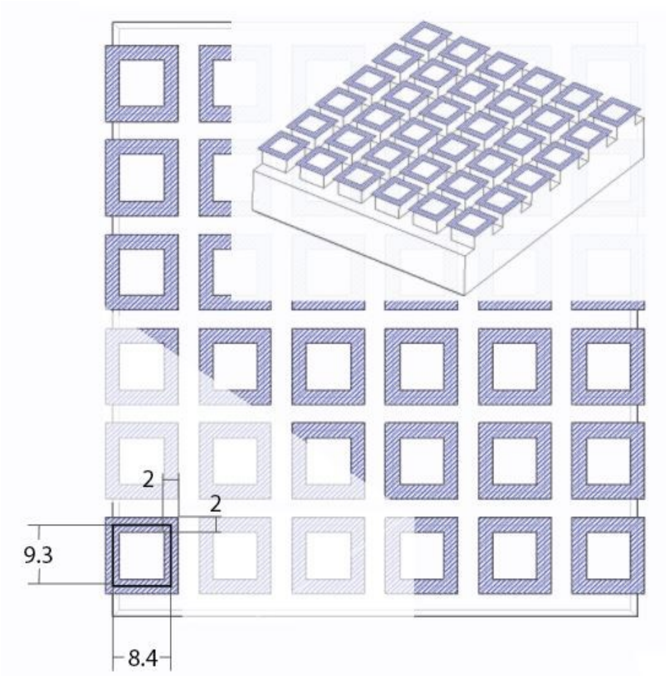



**Figure 5. The estimated effective area of the knobs is shown in blue.**

**Table 3. Evaluation of the number of effective stud impacts in the current over-run test with three different studded tyres. Partial impacts of stud have been considered in the calculation by extending the edges by 1mm.**

| ***Stone sample*** | | | | |
|---|---|---|---|---|
| Area of the sample [$mm^2$] | Area of the knobs [$mm^2$] | Knob ratio | Effective area of the knobs [$mm^2$] | Effective knob ratio |
| 7,084 | 4,231 | 0.60 | 2,549 | 0.36 |

| ***Tyre*** | ***A*** | ***B*** | ***C*** |
|---|---|---|---|
| No. of studs on a tyre | 190 | 130 | 96 |
| No. of studs per one circumference meter | 96 | 65 | 48 |
| No. of studs that impact the area of the test samples (1 roll-over) | 7.37 | 5.04 | 3.72 |
| No. of studs that impact the area of the knobs (1 roll-over) | 4.40 | 3.01 | 2.22 |
| No. of studs that impact the effective area of the knobs (1 roll-over) | 2.65 | 1.81 | 1.33 |
| **No. of effective impacts during the test** | **1,061** | **726** | **536** |

Several methods to increase the wear in the over-run test have been developed at VTT. By this, the resolution power could have been improved with as few roll-overs as possible. Currently, 200 over-runs take around 3 hours of constant driving so it has not been considered practical to increase the number of them. In addition to high speed and edge cleaving, test stones are kept wet during the test (see Figure 6). Due to the stone frame, samples stay under water almost constantly. Compared to dry surface of pavement, a wet surface wears around 1.5–3 times more. However, it has not been confirmed that the test samples in the over-run test behave in a similar way (Unhola, et al., 2016). Anyway, stones are weighed as "dry" which causes issues with the definition of "dry". The handling procedure before and after the actual test, over-runs, is complex as was seen earlier in this chapter. Stone as a natural material absorbs moisture and drying it to the level of "absolute dry" (moisture = 0%) is realistically impossible.

Reference stones were launched in order to avoid issues with "dry" stones (Unhola, 2015). Reference test stones similar to real ones go through the whole test procedure except actual over-runs (washing, drying, weighing, etc.). Based on the weighing of reference stones, a reference correction can be done – an example of this is seen in Appendix 3. Thus, this part of the procedure is performed just for compensation on changes in moisture. By five reference stones used, the error occurred due to different moisture levels is eliminated, at least in principal.

The weigh differences of the stones before and after the over-run test are minor: the maximum total wear of five pieces of stone (one row of stones) can be around 1g while the mass of those pieces together is around 1.5kg. Therefore, it is crucial to handle the stones carefully: no wear or cracks are wanted other than within the over-runs. In addition, the moisture issue demands elaborate descriptions regarding the handling of stones during the test procedure. Trafi has drawn up a detailed test method description to avoid differences between separate recognised experts or laboratories (see Appendix 1). Nevertheless, the handling of stones is surely one thing causing systematic and random errors between test laboratories and thus, it is certainly an important question to research within this thesis.

As noted, the main issue seems to be differences between results produced by different recognised experts. Some comparison tests commissioned by Trafi, for instance, have been performed, and divergent test results have occurred while testing the same tyre-stud combination by different testers. Although the test method description presented in Appendix 1 is quite extensive and detailed, some improvements should be implemented in order to reach comparable results within all recognised experts.

**Figure 6. Water coming from the line inlaid in pavement keeps the test samples under water, and water is applied also when conditions are rainy and wet like in the situation in the figure.**

## 2.4 Pavement wear

### 2.4.1 Factors

Multiple factors affect pavement wear by (studded) tyres. Some of them are widely studied whereas the others' impact on wearing mechanism is unknown or uncertain. The most important factors are presented here shortly. Factors are divided into four different categories to clarify the complex field of variables, and also to show that reducing road wear is not only a question of development of studded tyres. Some mathematical models with multiple variables (out of which some are presented here) exist both for the tyre specific modelling and the total road wear or particle concentration modelling (e.g. Jacobson, et al., 2007; Gustafsson, et al., 2015), but they are limited out of the scope of this thesis.

Regarding all factors, it is notable that the traffic volume and the share of studded tyres have a great impact on total wear. The constantly increasing number of cars and kilometres driven set even more demands not only for studded tyres but also for road network and maintenance. Traffic today differs from what it was some decades ago. Longer commutes, for example, have increased volumes on highways that are commonly well maintained. On the other hand, however, long distances from inland to coastal areas, for instance, also mean greater variation in weather conditions within a single trip. This is something that brings up new challenges both for customers choosing whether to drive with studded tyres and for traffic planners defining road maintenance levels.

**Properties of a stud and a tyre**

Traditionally the road wear effect of studded tyres has been controlled by setting limit values for different dimensions of studs and their setting onto a tyre. Typical dimensions in Finland (Table 1 on page 21) are similar to those elsewhere, in general. In addition, the shape of a stud is not to be hollow and a pin of the stud is not to be sharp (Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003).

According to Kupiainen, et al. (2011), an increased mass of a stud and a number of them on a tyre increased resuspended road dust in a clean laboratory environment, and thus, also road wear was estimated to increase. Differences at low speeds did not come up in this study, but when testing at high speeds (70–90km/h), clear trends regarding these factors were found. This seems natural since the vehicle speed affects wear as can be seen later (Vehicle factors on page 31). Also Gustafsson et al. (2015 pp. 25–32) and Gültlinger et al. (2014) concluded significantly higher concentration of particle emissions on tyres with more studs. However, one should note that tyres with almost twice as many studs (compared to traditional Finnish legislation) are sold in the market and have been approved by the over-run test. Thus, it seems that the effect of large number of studs can be compensated by other properties of a stud and a tyre.

VTT Technology Research Centre of Finland (1986 pp. 11-12; 1987 Appendix 4; 1989 p. 9) has found a clear dependency on the mass of a stud and road wear. According to them and several other parties (e.g. Gültlinger, et al., 2014) the dependency is directly proportional: doubling a mass of a stud doubles the amount of wear. The dynamic impact energy of a stud is here a key variable, and according to the basis of kinetic energy, it certainly is directly proportional to a mass. Although the experiments of VTT were conducted relatively long time ago, their relevance is to be considered feasible. It is worth noting that these studies have been made using the over-run test method based on which the test examined in this thesis has been developed. On the other, also controversial understanding has existed: Grönfors (1975 p. 51) has mentioned that the mass of a stud has no or very limited effect on road wear. However, as a conclusion, the mass of a stud is generally considered as the most important single factor that has been proved to affect road wear (Unhola, 1995 p. 19; Unhola, 1997 p. 13).

Unhola (1995, 1997) has studied the effect of stud protrusion and stud force on road wear. By reference tests, he has found that the protrusion of a stud has a slightly positive effect on road wear. The correlation is not completely clear, not to mention linearity, and differences between studies exist. In 1995 (pp. 17–18) the wear increased only 5–9% when increasing the protrusion by 50% from 1mm, whereas in 1997 (p. 12) the increase was estimated to be nearly 40%. Nevertheless, other differences on tyre and stud properties were not eliminated from the result in 1997, so these percentages cannot be directly compared. Another study has estimated protrusion and dynamic impact of a stud to be directly proportional (Grönfors, 1975 p. 55). Some positive correlation between stud force and road wear was found in the same studies of Unhola: in 1997, the dependency was even strong, while in 1995 as clear results could not be produced as only uncertain estimation of the positive effect was done. On the other hand, significant increases on particle emissions have also been found when increasing stud force (Gustafsson, et al., 2015 p. 34), and as one criterion in legislation, it is considered a significant factor.

What seems to be even more important is that clear evidence of the type of a tyre and the shape of a stud has been found (VTT, 1987; Unhola, 1997). A sharp head of a stud increases point pressure – stud force remains the same – towards pavement and thus, road wear can be estimated to increase. A hollow shape has a similar effect. An increase in hardness of material of a tyre rubber (especially under a stud) has been found to decrease PM concentration (Gustafsson, et al., 2015 p. 34), which is seen as controversial comparing general and intuitive understanding: the smaller an elastic constant of the rubber of a tyre (i.e. the softer rubber) is, the less energy is required for a stud to intrude into a tyre and the lower force is applied towards road surface. However, Gustafsson et al. (2015) have used a carousel test (see introduction in chapter 2.5) and the softer rubber has been estimated to enable more scratching due to a strong turn-slip effect and vice versa. Nevertheless, together with the material of a tyre, the material of a stud, flange of a stud and setting of studs on a tyre have also been found to have more effects than thought (Unhola, 1997). Anyway, these matters support the idea of the use of the over-run test (or similar) as it enables innovative solutions on studded tyre technology and one does not need to be limited to strict dimensional threshold values when designing studded tyres.

Besides the factors mentioned above, Unhola (2004) has studied the effect of the pressure and the profile of a tyre on pavement wear. He has concluded that an increase in pressure – which has taken place during recent decades – increases the road wear: around 10kPa or 0.1bar increase on pressure results in a 4% increase on road wear. It could be considered that a (high) over-pressure would decrease the wear since the studs are not to be assembled on a central area of a tyre's contact surface according to the traditional legislation. This is a hypothetic matter as over-pressure is not an optimal or desirable situation due to uneven wearing of a tyre, for example. On the other hand, a decrease in tyre profile – which has also taken place during recent decades – decreases the road wear by 10% per each drop of 0.10 in profile. (Unhola, 2004 pp. 17–18)

One should notice that significant differences on study results may occur depending on test method: Unhola and VTT have mainly conducted over-run tests with real cars in outside conditions driving straight with constant traction, whereas studies in Sweden (e.g. Gustafsson, et al., 2015) have been conducted in laboratory conditions using a so called carousel road simulator (see chapter 2.5) where turn-slip motion in contact between tyre and road is continuous, which does not reflect real driving conditions. Another note concerning real wear in real world and its development over a time depends strongly on the wearing of a tyre and studs themselves. The basis of a design is usually to get the stud and the tyre to wear consistently so that the protrusion would be the same. However, all properties of a tyre change when it is used and these road wear tests always measure the wear of a new tyre.

**Vehicle factors**

The mass of a vehicle with studded tyres seems to cause a linear change in road wear (Unhola, 2004 p. 19; VTT, 1989). Two effects of increased mass or wheel load can be defined: (1) the stud force increases (if the pressure of a tyre is adapted) and (2) contact path size increases (if the pressure of a tyre retains on the same, lower level). Both these effects cause more road wear and thus, whether the pressure is adapted or not, road wear increases.

The speed of a vehicle is a difficult factor regarding its dependency on a road wear. It is clearly visible that an increase in speed at high speeds (>80–100km/h) increases road wear significantly (Unhola, 1997; Kupiainen, et al., 2011; Unhola, 2004 p. 20). However, they are not uniform in conclusions of how the level of wear is affected at lower speeds. Unhola (2004 p. 20) estimates that the lowest level of the road wear is reached at 70–80km/h and the wear is slightly increasing when reducing speed from that. On the other hand, Gustafsson (2008) and Kupiainen et al. (2011) have come to the conclusion that particle emission and road wear increase linearly in function of speed. Almost similar estimation has been given by Grönfors (1975 p. 55): dynamic impact energy is proportional to the speed's power of 1.2–1.3. Heikkinen (2012 p. 108) has studied the road wear at urban speeds: he found direct dependency between the road wear and speed but concluded that the wear due to studded tyres is significant only at speeds over 60km/h. According to the study conducted by the European Tyre and Rubber Manufacturers' Association (ETRMA), it seems that tyre model affects the detected dependency regarding the vehicle speed as road wear of some tyres has been at the same level at both tested speeds 50 and 100km/h whereas the wear of some other tyres has increase 50% when driving faster (ETRMA, 2016). However, higher speed affects not only road wear but it also causes stronger effect of resuspended dust.

The drive of a vehicle is not regulated in the over-run test method description, but it is included in the test through the limit for the change in stud protrusion before and after the over-runs. Primarily, the drive of a vehicle may have an effect on wear as the traction force affects wear, too (Gültlinger, et al., 2014). Here in the over-run test, the question seems irrelevant as the vehicle is commonly rolled over the test samples freely without traction force. In a real traffic environment the drive may have relevance: the traction force on a driving axle in a two wheel drive (2WD) vehicle is basically double as high as in a four wheel drive (4WD) vehicle. If the traction force affects road wear linearly, both 2WD and 4WD vehicles should, in principle, have the same wearing effect, but if the relation is not linear, the difference in wear caused by the drive may be found. However, a secondary effect of a change in stud protrusion is present in the over-run test, too: a front wheel drive (FWD) vehicle's front tyres need to transfer both longitudinal and transversal forces as they do the steering and acceleration (mainly also deceleration). In rear wheel drive (RWD) and 4WD vehicles these forces are distributed more evenly and smaller increases in stud protrusion are expected. Thus, with smaller protrusions wearing should also be lower as was mentioned earlier.

The transmission type (automatic or manual) can be considered to have no effect on wear in the over-run test as the speed is constant. On the other hand, in practical driving conditions it may have a slight effect due to "softer" or "gentler" gear shifting of automatic transmission. However, the overall effect of this is negligible compared to other factors.

**Properties of pavement**

The most used pavement types in Finland are hot-mixed asphalt-concrete and mastic asphalt with 93–95% of aggregate and 5–7% of bitumen. Aggregate mainly affects wear resistance whereas bitumen only has a minor effect. Gustafsson (2008b) has come to the conclusion that granite – that is commonly used in Finland – as aggregate results in a 70% higher $PM_{10}$ concentration compared to quartzite as aggregate. $PM_{10}$ concentration differs from the total wear as particles in other sizes also belong to the worn material. Nevertheless, this gives some guidelines regarding effects of material choice.

Gustafsson (2008b) also studied the effect of aggregate size of a pavement. Pavement with smaller stones led to lower $PM_{10}$ concentration which seems controversial against other studies. Based on literature (e.g. Heikkinen, 2012 pp. 20–21) it is a generally known fact that pavement with larger aggregates leads to lower wear. In addition, so called silent pavement materials – which are mainly made out of smaller aggregates – are generally considered to wear more than “normal” materials.

Considering pavements, it needs to be underlined that by optimizing pavement materials and improving structures the wear resistance of commonly used pavements has been improved during recent decades, and the control of total road wear is not only to tyre technology’s credit, but also to the pavement development’s credit. A good example in Finland is the research program of asphalt pavements (ASTO-project) in 1987–1992 that was unprecedented as for scale.

**External factors**

As noted before in chapter 2.2, rutting causes most concern considering renewing of pavement. As one external factor, traffic planning can be considered significant. By traffic planning, at least the following things – that have been recognised to affect road wear (Heikkinen, 2012 pp. 112–114) – can be optimised:

- width of a lane: not everyone needs to drive in same grooves
- changes in a state of motion, such as:
    - (tight) bends
    - traffic lights etc. that cause decelerations and accelerations
    - (strongly) hilly road profiles that demand more traction and braking
- grinding due to camber of a road, for example
- speed limits.

Ambient conditions are almost impossible to control, but they have an effect on wear. Wet surface of road wears around 1.5–3 times more than dry road (Unhola, 2015). It is noticeable that this phenomenon may not concern the over-run test, though, where pure stones are used (Unhola, et al., 2016). According to Gustafsson (2015 p. 34) temperatures have clear effects, too: a higher tyre temperature decreases particle emission concentrations significantly, whereas higher air temperature seems to increase concentrations. Conditions on roads are mainly influenced by snow ploughing and salting which both increase wearing indirectly, but more importantly, improve safety. It is clear that pavement on a road covered by thick snow or ice layer does not wear.

Traffic politics has – or can have – a great influence on road wear. The level of the use of (certain kind of) studded tyres can be controlled by promotion, benefits, banding or taxes, like the level of the use of private cars overall. In addition, several other factors may have multiple and complex ramifications. Anyway, a lot can be achieved by laws and regulation if one likes to devote to it.

### 2.4.2 Mechanism

The understanding of the mechanism of pavement wear on a detailed level helps the research on factors influencing on it. There are multiple aspects regarding the mechanism. Within the over-run test, it is necessary to understand how a certain stone sample behaves under a tyre and studs: what happens when a stud impacts a stone, is a scratch a part of wearing and how a stone is cleaved according to grains on edges? On a general level, which is certainly more important, the question is whether the wear in the over-run test represents and correlates with the wear of real pavement materials in real life. As material, pure granite and asphalt (real pavement material) are quite divergent, but it has been stated that the wear in the over-run test – cracked/cleaved pieces composing major part of it – is justified because cleaving is dominant within real pavement that is mostly composed of stone that cleaves in similar way (Unhola, 2015). However, it needs to be noted again that the wear in the over-run test is some 10 times greater than in real life due to several reasons discussed earlier.

Gültlinger et al. (2014) have studied the mechanism of road wear at Karlsruhe Institute of Technology (KIT). They have presented the theory of behaviour of studs on a rotating tyre and different phases during contact with road surface. According to them, six distinguishable phases can be defined as shown in Figure 7. The first phase is the most significant considering wearing especially at high speeds: the impact. The pin of a stud hits the road, and the energy of this impact depends mainly on the stud mass and vehicle speed. More detailed explanation can been found later in this chapter.

During the second phase, a stud is intruded into a tyre (Gültlinger, et al., 2014). The intrusion depends on properties of the tyre and road surface: on soft ice or snow, a stud is preferably thrust into a road surface whereas on asphalt a stud penetrates into a tyre to be on even level with the rubber surface. The way a stud intrudes into rubber depends on load for a stud that is most likely asymmetric and viscoelastic behaviour of rubber, for instance, which means that a stud may move longitudinally already during this phase (Lindén, 1979 pp. 106–108). Lindén has studied heavy vehicles in lower speeds so that these findings are not straight comparable with the over-run test where high speeds are used. In addition, the tyre technology has developed much since those days.

The third phase is more or less stable since adhesion is made up on the one hand between road surface and the stud, and on the other hand between road surface and rubber. The fourth phase, transition, is due to different friction properties of the stud and rubber: rubber tends to slide so that a stud stuck on a road surface gets into an angle and a displacement is arisen. This phenomenon continues till the stud angle in which the stress exceeds a limit. Then also the stud starts to slide (phase five). In lower speeds, it has also been observed that the movement of a stud in a road contact may be periodic so that it slides a bit, then stops, then slides again et cetera (Lindén, 1979 p. 106). Finally, during the snap-out phase, the rubber and the stud lose contact with a road surface. The load on the stud is reduced and thus, the intrusion into a tyre is reduced. Additionally, if any displacement between a stud and rubber existed, now it evens out to the normal situation. (Gültlinger, et al., 2014)

The behaviour theory of a stud in a contact patch of a tyre defined by Gültlinger et al. (2014) is one of few such theories. However, it seems to represent reality at least partly. Phenomena observed when inspecting the trace caused by a stud on a road surface support some phases of the theory (Figure 8). The trace includes an impact and scratching that can be considered to be resulted from phases 1 (impact) and 5 and 6 (scratching). It is difficult to confirm the behaviour between these phases. Lindén (1979 p. 134) has also concluded that the behaviour of a stud in a contact with road is complicated and it cannot be calculated with only a few variables. Today, more complex mathematical models would be enabled, though.

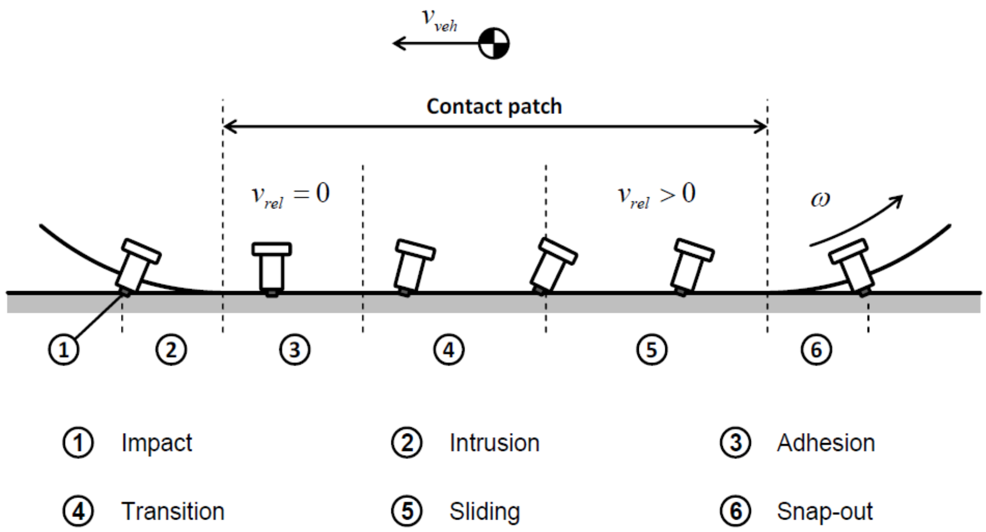



**Figure 7. The estimated behaviour of studs on a rotating tyre against the surface of road: $v_{rel}$ refers to the velocity of a stud in relation to tyre surface, $v_{veh}$ to the velocity of the vehicle and $\omega$ to the angular velocity of the wheel (Gültlinger, et al., 2014).**

According to Gültlinger et al. (2014), three different types of wearing mechanism can be considered: (1) impact damage, (2) scratching damage and (3) compressive damage. They have come to the same conclusion as Unhola (2015), that impact damage is a dominant wearing mechanism at high speeds. In Figure 8, different traces of a stud can be seen: at 60km/h the impact damage is hardly notable whereas at 120km/h it is nearly the only mechanism shown. This has been justified by the kinetic energy of a stud (Gültlinger, et al., 2014). Dynamic impact energy was the term used earlier (chapter 2.4.1) meaning the same thing, and in theory it is proportional to the square of the speed. The speed difference between a stud and road surface can be defined according to Figure 9 (more detailed calculation based on this is seen in Appendix 2). The energy due to the speed difference is absorbed either into the deformation of rubber in a tyre or into the damage of a stud or road surface. Since the material of studs (especially pins of them) is remarkably harder than that of a road, it is mainly the road that is damaged. Kinetic energy is also proportional to mass, and lightening the mass of a stud is proved in many studies to decrease road wear. Thus, the limits for stud mass in traditional Finnish legislation is well justified.

**Figure 8. It can be seen in traces of a stud on stone at different vehicle speeds – 60-80-100-120 km/h respectively from left to right and from top to bottom – that the effect of impact is dominant at high speed while scratch can be considered as main mechanism at lower speeds. (Unhola, 2015)**

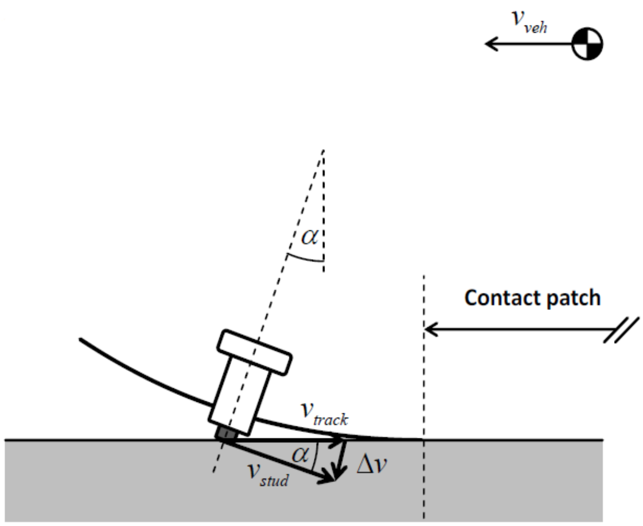



**Figure 9. Schematic picture represents the speed difference and the angle of incidence when a stud impacts a surface of a road: $v_{veh}$ refers to the velocity of the vehicle, α to the angle of incidence of the stud and $v_{track}$ and $v_{stud}$ to the velocity of the track and the stud, respectively, in relation to the vehicle's coordinate system. Δv represent the difference in velocities of the track and stud. (Gültlinger, et al., 2014)**

## *2.5 Alternative test methods*

The over-run test method described here is not the only test for the road wear measurement. Other methods have been studied also in Finland during recent decades, but for Finnish purposes, the over-run method has been evaluated to be the best (Unhola, 2015). Some other methods are introduced here briefly.

**Quantitative methods**

The traditional procedure regarding studded tyres in Finland can be classified as a quantitative method. Today, many of the moderate price studded tyres with "standardised" studs come into the market through this procedure. The method, in its simplest way, is based on a few quickly measured dimensions of a stud and their setting onto a tyre. The dimensions here have been selected based on evaluation of the most important physical properties regarding road wear. This method gives little room for innovative solutions being a compact and affordable way to bring a tyre into the market. Therefore, a similar approach is widely used worldwide.

With regard to other quantitative methods, some mathematical road wear models in some form could be the next step after the traditional dimension based method described above. A more complex model would give more space for divergent solutions. The number of studs or their weight could exceed the normal limits if some other figures guaranteed a low enough wear: the same idea as in the over-run test enabling innovations, but dimension-based model would simplify and speed up the procedure. However, models are still more or less imprecise as all factors of the real world cannot be taken into account. In addition, developing a model that would reflect the reality at least to some degree, is difficult and all but unambiguous.

**Laboratory tests**

A road wear test in a laboratory can imitate reality or it can be kept just as stripped as possible. Within the first alternative, two basic types of test are used successfully: vertical and horizontal circle tracks. The Swedish National Road and Transport Research Institute (VTI) has a horizontal road wear track, a so called carousel, where four tyres are driven by a machine like carousel in a circulator track covered by pavement (see Figure 10). The device enables the use of real tyres on real pavement materials without constant human effort, which makes it easy to increase the number of roll-overs. On the other hand, the device itself is expensive, settings are laborious and results are not comparable to real driving conditions due to the strong, constant turn-slip motion between the tyre and pavement. (VTI, 2016)


**Figure 10. The horizontal testing track – a carousel – of VTI (Gustafsson, et al., 2009 p. 14).**

Another potential and similar kind of test method has been developed at Karlsruhe Institute of Technology (KIT): the vertical road wear track, so called inner drum test bench (see Figure 11). A 3.8 meter drum is covered inside by any desired material that, though, obviously needs to be bent. The drum and the tyre rotate while the tyre is under vertical load against the surface of the drum, and while a traction force is applied through the tyre and/or the drum. This set-up enables various tests including different speeds, traction forces, turning angles, surfaces et cetera. With this method, the main disadvantage of the carousel test, the turn-slip effect, can be avoided and thus, very realistic results can be produced although the surface is bent and not planar like in the normal driving conditions. Otherwise the test method is presumably expensive and needs some effort for preparations. Bent pavement surface is difficult to make, which also causes some extra costs. (KIT, 2016)

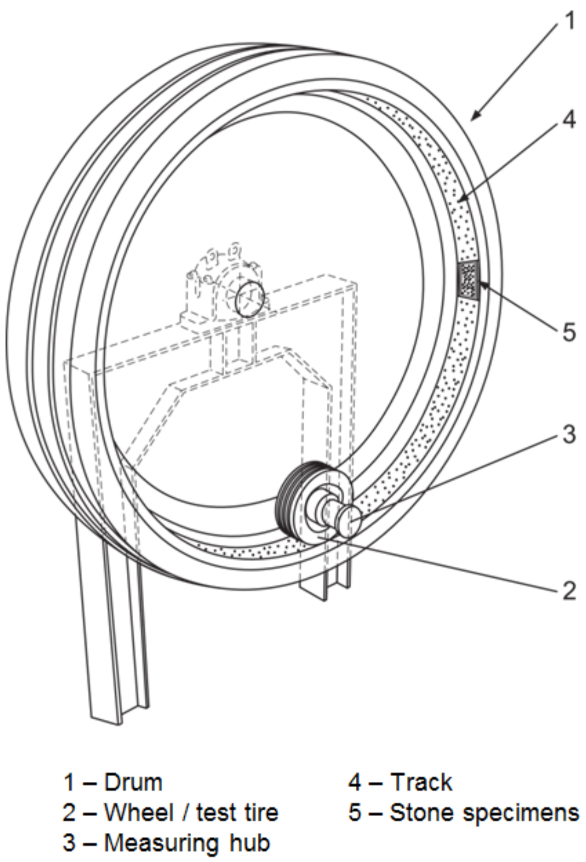



**Figure 11. The inner drum test bench of KIT (KIT, 2014).**

The two methods introduced above aim at representing the reality whereas truly theoretical laboratory tests exist for more specific phenomena of wearing. The most current and known method is the standardised Prall test that also includes a test for studded tyres but is primarily used for material testing (SFS-EN 12697-16, 2004). Additionally, Tröger and Ball mill tests, for instance, were in use some decades ago. As mentioned, all these methods are for research of specific, individual factors influencing the wear of certain material and they do not represent the real road wear of studded tyres since all factors around the phenomena of “the road wear of studded tyre” cannot be included in any of these test methods. Thus, one fundamental problem is that real tyres cannot be tested. (Unhola, 2015)

**Methods comparable to the over-run test**

Some radical developments on the over-run test – things like change of the material of test stones, over-runs with a trailer with multiple axles or extremely high load on tyres – could be considered. These manoeuvres would increase the total wear as such, but they would also need more preparations and resources. In addition to these, one reasonable way to control the variation in conditions would be to use reference tyre in every test. The over-run test has been developed over the years and these kinds of changes have not been suggested widely and they have not been considered genuine alternatives. However, all possibilities should be kept in mind, and some fundamental improvements are also considered in this thesis.

Over the years road wear has been studied in Finland with the help of test roads. Both full scale test roads and mini test roads have been under research (Unhola, 2015). In a full scale test road, the overall area of a section of the road is covered with certain pavement and the wear of this is studied, usually at least in intervals of months. The idea behind mini test roads has been to cover just a narrow part of the road – on the line where tyres roll over – with certain pavement. Costs and controllability with mini test roads are more reasonable, but both methods are though very time consuming and laborious as they need much preparation (Unhola, 2015). Vehicle factors cannot be controlled and nothing on laboratory level may be reached. On the other hand, these test methods represent real driving conditions and thus, produce valuable data regarding the total wear of roads. Wearing effect of individual tyres is impossible to study, but pavement materials can well be under research, for instance. Regarding testing in real traffic environment, also so called vacuum method has been in use: material worn from pavement is tried to be sucked or vacuumed right behind a tyre and then analyse the gathered material (amount and type). The problem may occur due to uncontrollable conditions, unknown sources of dust and expensive equipment (e.g. Unhola, et al., 2004 p. 29).

# 3 Analysis of the test data and procedure

## 3.1 Description

The analysis part of the thesis is divided into three sections depending on a nature of reference material. In the first section, the numerical data regarding the actual and complete over-run tests received from all of the testers (the task force) and other sources is analysed. In addition, the task force has provided data about the handling procedure in the over-run test related to weighing and weight differences between separate phases during the procedure: how big the weight loss in the stone washing is, for example. In the second section, a theoretical analysis is conducted based on general facts and the laws of physics. The behaviour of moisture level in the stone and the environmental conditions affecting dimensions of a tyre are inspected more closely. The over-run test as such is not included in this section as the situation and possible error cases are analysed outside of the test procedure. However, it is shown how errors may occur in the test. Variables that closely relate to tyre testing in general do not disturb but, on the other hand, a few assumptions make the calculation purely theoretical, and no absolute numerical values can be given. In the third section, a qualitative analysis is conducted based on the test method descriptions and the work instructions provided by each of the testers. Interviews and impressions among different parties are also mirrored in this reflective section. In addition, support to the presented matters is provided by the reference material.

The first section composes a significant part of this chapter. Results are shown in graphs and charts but also by means of statistical calculations. The field of variables in the over-run test – and in tyre testing in general – always causes difficulties due to its infinity. Tyre testing is never static, and comparable results usually require reference tests. However, the number of variables gathered to conduct the analysis was around 50 per each test. Not every variable was available from every test which caused some limitations regarding statistical confidence. The total number of available tests was around one hundred but due to three different sources of data – referred to as task force data, comparison test data and type-approval data – the analysis was conducted in parts. Thus, the test conditions in each test analysed together could be as stable as possible, but on the other hand, the number of tests in one analysis suffered from this. Some conclusions were also made from the entire test data, whenever it was feasible.

As described earlier, most of the data utilised in the analysis presented in this paper has been received from the task force. The task force has performed its own analysis based on the same figures, but the purpose of the thesis is to prove the conclusions and to detect new observations. This paper is also important because of its objectivity as the thesis is commissioned by the authority, Trafi. Until now, the conclusions based on the most recent data have been made by the testers only.

The data received from the task force composes a major part of all numerical data utilised here (see Figure 12). Thus, it was a primary prerequisite for this thesis. The data mainly provided most of the 50 variables, but tests with only few reported variables also existed. In some sections, the number of tests with proper variables recorded or reported is, therefore, not satisfactory.

The task force data has been defined confidential by the testers, and it can be considered reliable and independent: every tester is committed to the project and to sharing this information with each other and Trafi. The material has been produced for the development of the over-run test and it includes results with limit-exceeding values, too: only tests where stones have been cracked or something as dramatic has happened have been left out. The data has mainly been produced in 2015 so the test procedure has fulfilled all the latest requirements of the over-run test in the type-approval procedure. In addition, this data has been produced with similar tyres of the same size. Therefore, it is processed as the most valuable data available. On the other hand, different types of stone samples (see dimensions in Table 7 on page 54) have been used when conducting tests, and the tests with different stones are generally not comparable with each other.

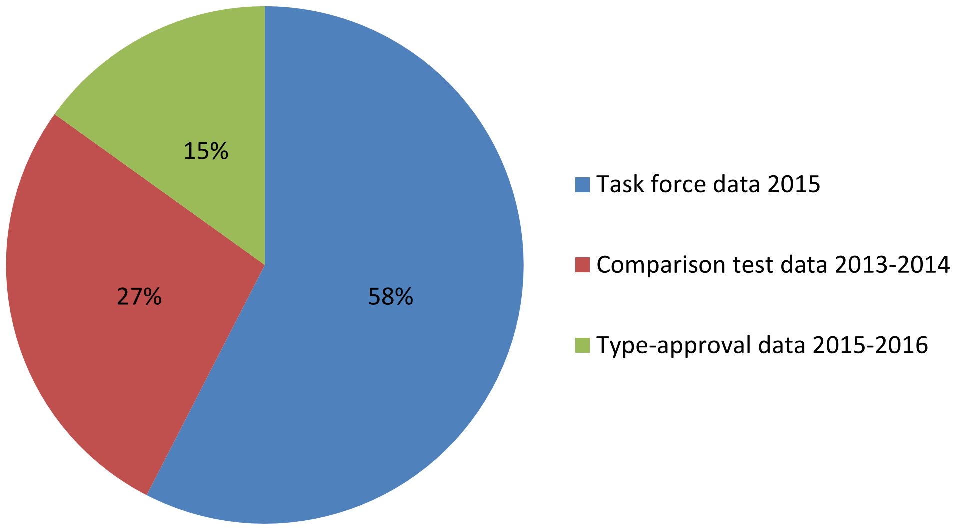



**Figure 12. The data received from the task force composes a major part of all utilised over-run test data. (Task force, 2015; Trafi, 2014b; Trafi, 2016b)**

In addition to the most recent data, the members of the task force have conducted several comparison tests commissioned by Trafi. The data available has been produced in 2013–2014 and it has been gathered and organised by Trafi. This comparison test data corresponds to the task force data described above, but due to the changes and a more detailed specification of the test method, this data does not represent the most recent situation. However, the changes in the method description were evaluated not to radically affect results, and therefore all this data could be utilised in the analysis, too. The main differences were found to be certain lacking figures, the reporting of which has later become obligatory and some specifications of the procedure. Comparability within this data resource seemed to be feasible as the tests were conducted by two known tyre types and sizes: the number of specimens with the same tyre was feasible enough to perform numerical analysis. In many sections, different tyres are analysed separately.

More different numerical data of the over-run test was available in the form of type-approval certificates and test reports on them. Basically, all the same figures are presented in those papers, and unlike with the earlier presented data, the form of figures has been defined so that it has been possible to ensure that all the necessary values have been reported. The most recent test report template was taken into use in 2015, though, and before that the figures presented in the test report of type-approvals varies a lot. Therefore, it was decided to take the type-approval documents from 2015–2016 into account in this paper. The type-approval data as such is considered to be comparable with other data as it has been produced by exactly the same test. However, one should note that the type-approval data only includes tests and results that fulfil all the requirements for the conditions and road wear. Thus, tests where the reference correction or the final result, for example, have been too large have already been filtered off. This does not make the existing type-approval data incorrect, but it changes the nature of the data as only "the best" figures are shown. This fact is taken into account whenever its effect has been considered noticeable. In addition, the figures from all the rest of the data used in the analysis mainly fulfil the requirements. Therefore, the type-approval data – that composes only a small part of all data – does not deviate much from the other data. A fact causing problems in several analyses is, though, that every test included in this part of the reference data has been produced with different tyres in varying sizes. This limits the usability of the type-approval data, but when concluding a broader picture, this data was seen useful and, therefore, it was taken into the analysis.

To unify the existing data, it was decides to include only tyres in load rating class 600–800kg in the analysis. This corresponds to load indexes 90–100. A clear majority of tests was performed within this class so the decision to leave the others out was reasonable. Variation within a certain class may also exist as the load index and tyre size ranges are wide. Normally, the load index class 90–100 includes tyres in sizes between 195/65R15 and 225/45R17 which means different sizes of footprints, for instance. However, the task force data was produced with similar tyres, and only two different tyres were used in the comparison tests, so only the type-approval data included figures produced with divergent tyres.

The primary objective was to find systematic trends against different variables, and with the help of that, to recognise phenomena that cause these systematic differences not only between the recognised experts but also within one tester. Different phenomena were highlighted against different variables to detect these trends. In addition, it was also important to find out the trends in conditions that did not seem to have any effect to give away useless limitations and requirements for the conditions and to forget new restrictions for these variables. In addition, phenomena that were not clear due to lack of proper data or too scattered results, were listed so that further study can be concentrated on such matters. The hypotheses formed with the framework of this paper are presented in Table 4. Regarding the final road wear values that were inspected as such, the confidence limits of these figures were evaluated within a certain group. Whenever the confidence limits are shown below, it is assumed that the figures are normally distributed and the limit is a 95% confidence limit if nothing else is informed.

Due to various variables included in the over-run test, the data utilised is often scattered and the hypothesised phenomena cannot be recognised. The conclusions based on these analyses are to be made cautiously and the possibility of errors always exists.

**Table 4. The hypotheses for different variables analysed in the paper based on the literature and experience.**

| Variable | Hypothesis |
|---|---|
| *Temperature increases (air, track, tyre)* | Road wear decreases |
| *Load on (the over-run side of) a vehicle increases* | Road wear increases |
| *Drive of a vehicle* | **4WD**: smallest change in stud protrusion/even share of traction<br>→ Lower road wear<br>**FWD**: largest change in stud protrusion (in front)/uneven share of traction<br>→ Higher road wear<br>**RWD**: in between |
| *Dry/wet test track* | a) Track temperature lower when wet track<br>→ Higher road wear<br>b) Change in protrusion smaller and friction lower when wet track<br>→ Lower road wear |
| *Stud force increases* | Road wear increases |
| *Stud protrusion increases* | Road wear increases |
| *Test stone dimensions* | a) Deeper groove<br>→ Higher road wear<br>→ Higher deviation<br>b) Longer knob edge length<br>→ Higher road wear<br>c) More knobs i.e. more knob corners<br>→ Higher road wear<br>d) Larger knob area<br>→ Higher road wear |
| *Testing company* | (Systematic) differences |

## *3.2 Statistical analysis*

### 3.2.1 Temperature

Today, the official over-run test method description requires reporting temperatures from three different objects: air, track and tyre. Air temperature is to be measured before the test in shadow and the allowed interval is 2–20°C. On the other hand, track temperatures need to be measured at the beginning, in the middle and at the end of the test. All these values must be 2–25°C. Tyre temperature measurement is also required but the method description does not set any limits for that. It needs to be checked three times during the test – in the same way as track temperature – from 5cm from a rim at the same spot every time. Tyre temperature is not included in this analysis due to limited data, and a justified conclusion can be made based on other figures as the tyre temperature follows the track temperature when driving. In addition, it has been noticed that the tyre temperature measurement process varies between the testers: for example the type of a meter and the time from stopping a vehicle to the measurement significantly affect the result so that the available figures would not have been comparable.

The effect of temperature was evaluated separately from the task force data and the comparison test data. The task force data including tests that were performed with the same tyre type every time was inspected in two parts (see Figure 13); tests conducted with

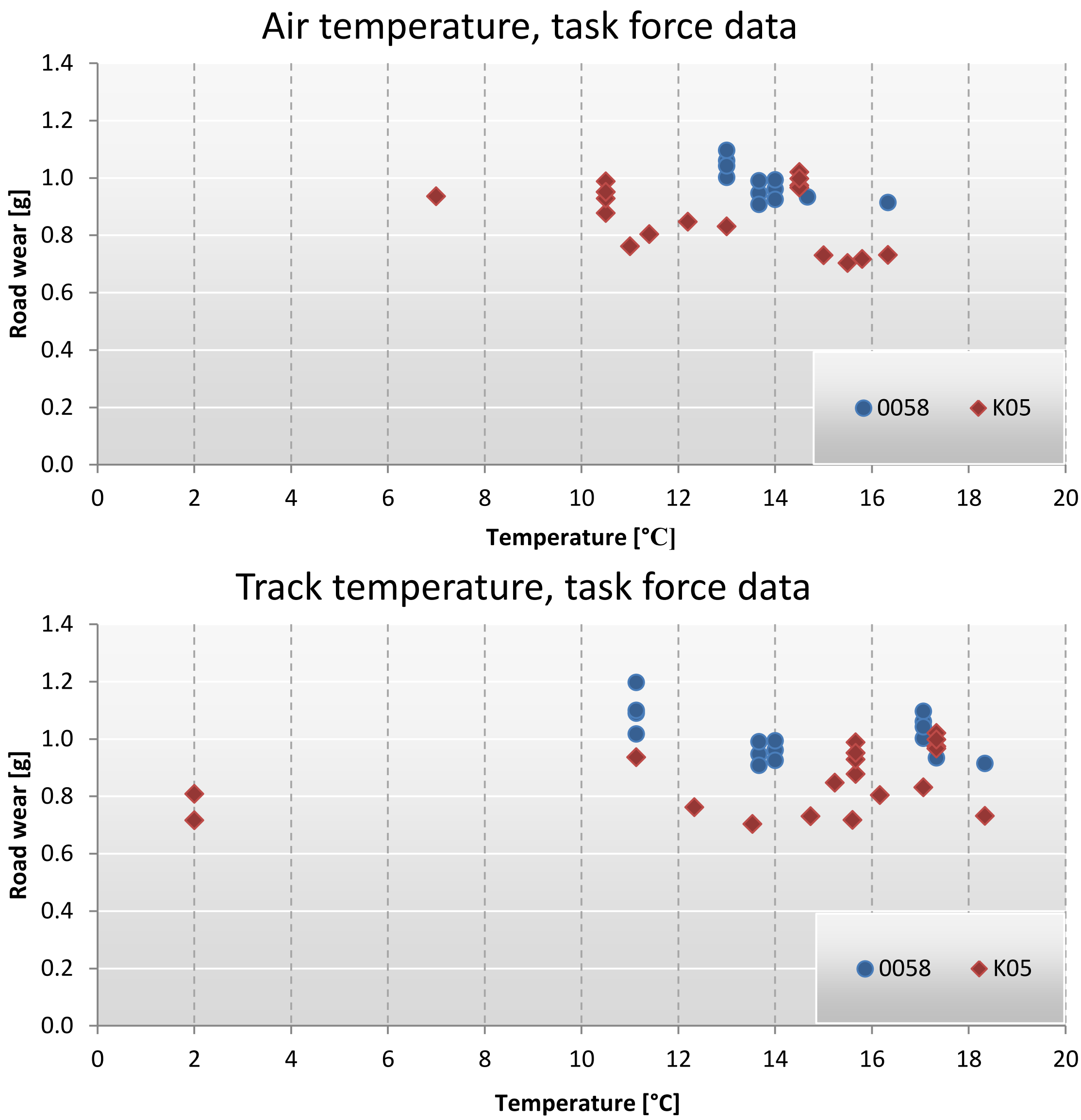
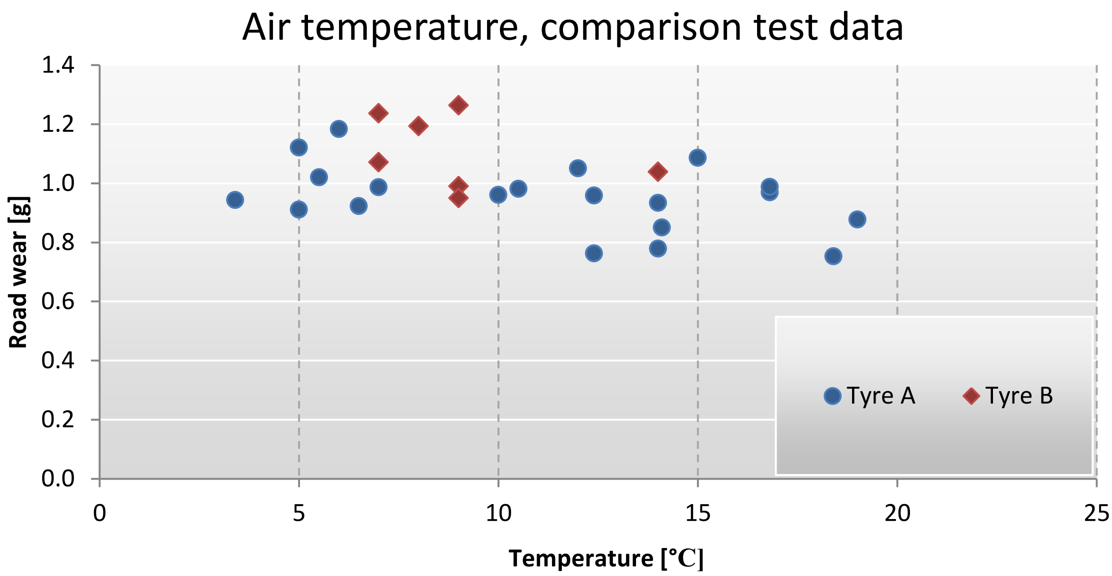



**Figure 13 a and b. Air temperature (a) shows a more uniform dependency than track temperature (b) against the road wear. (Task force, 2015)**

different stone samples were incomparable. A few coarse errors have been removed here and also later whenever it has been considered needed. The track temperature regarding a certain specimen in the analysis is the average of three temperatures or the only value reported.

The graph for the air temperature shows that the higher the temperature, the lower the wear – with the track temperature, the dependency does not seem that clear especially regarding the tests conducted with the K05 stone (see dimensions of the stones in Table 7 on page 54), and dispersion is large. With the 0058 stone the trend better follows the hypothesis. Similar results are shown in the analysis produced based on the comparison test data (see Figure 14). This data has been divided into two parts according to two different tyre types. Especially the tyre B data is very narrow as only seven specimens were available. However, when plotting a linear trend line for these and for tyre A, too, it is seen that the



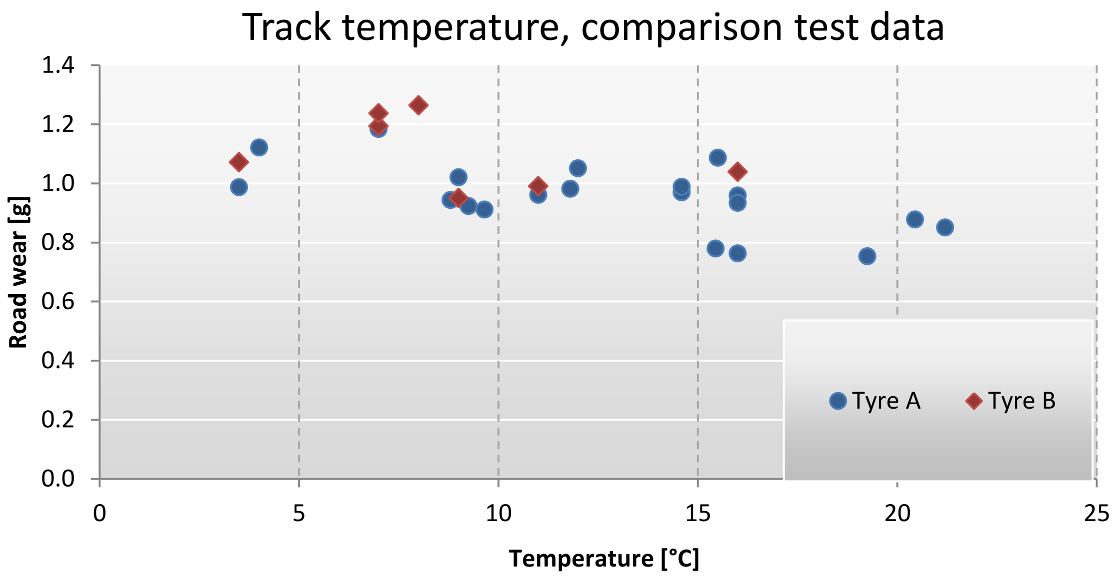




**Figure 14 a and b. Deductions only based on the data regarding tyre B may not be done but together with tyre A, the hypothesis seems to be true as a higher temperature results in lower wear. (Trafi, 2014b)**

effect of the temperature seems to be the same that was noticed with the task force data: the higher the temperature, the lower the wear.

It needs to be kept in mind that air temperature and track temperature follow each other so that graphs presented earlier look similar and they cannot be inspected individually.

When inspecting the temperatures, another weather-related variable should be examined: whether the track is wet or dry. In addition to weather conditions, some testers are used to watering their track before and during the over-run test if it otherwise were dry. The watering or wet track in general could be thought to have a lowering effect on temperature because of evaporation and the resulting heat binding or cooling. In addition, the temperature of water itself is commonly lower than that of a track. However, looking at the track temperatures in specimens with a wet track and those with a dry track, wet tracks were only 1°C colder than dry ones, on average. The averages were calculated based on all available results.

Wet track did not limit the highest peaks that would have been foreseeable, either. However, watering is not defined in the method description, so there are certainly differences between cases where a track is watered only at the beginning or several times during a test. The type of rain from the sky also differs a lot and wet track in the analysis means either watering or raining. In addition, the moment when the temperature is measured – just before watering or after that – has an effect. Therefore, watering seems not to be straightforward variable with only two possible values. A more detailed study on the watering effect with harmonised conditions would be needed to conclude a dependency, but from the physical perspective, watering should equalise the track and tyre temperatures when it is done uniformly and thus, stabilise the conditions.

The reasons why a higher temperature – in air or on a track – results in lower wear can be divided into two. First, temperature affects the hardness of rubber and thus, the stud force and its dynamic behaviour change: a warm temperature makes rubber softer. This is also a question of good design of performance in winter conditions: the colder the conditions are, the harder the ice on a road is, too – therefore the stud force should also increase in a cold temperature so that the stud can penetrate into the ice and provide a better grip. Even if both the stud force and the temperatures were reported in the data, no conclusions of a relation between these variables could be made because the stud forces are often measured in a laboratory temperature and not in field conditions in the driving temperature. Thus, the portion of the rubber temperature sensitivity on the effect on the wear cannot be determined.

The second point here is the temperature's effect on the pressure in a tyre. The pressure is defined in the method description, but the question is, how the temperature changes during the test and is the temperature the same during driving compared to the pressure measurement environment. The method description requires that the pressure is measured from a cold tyre, but again the definition seems loose. To put it shortly, a higher pressure shortens the footprint of a tyre and, thus, decreases the angle of incidence and the dynamic impact energy. Also the grinding time is shorter and possibly the final scratch of a stud is lighter due to the short contact on a track. More detailed evaluation of the effect of pressure is presented later in chapter 3.3.2.

### 3.2.2 Load

Primarily, tyres are divided into four classes in the over-run test method based on their load indexes. The inspected load index class is 90–100 corresponding to 600–800kg. The other classes are less than 600kg, more than 800kg and a light commercial vehicle class. In addition to the division, tyre loads are regulated in the test. First, the total weight of the whole vehicle needs to be 65–75% of the sum of the maximum load of each tyre. Second, the load for each tyre must be 60–80% of the maximum. Third, the difference on loads between right-side and left-side tyres on the one hand, and between front and rear axles on the other, needs to be less than 5% in order to ensure an equal share of load. These limitations are partly overlapping, but, for example, the limit for total load enables some 300kg difference in the inspected class, which may seem significant. The analysed figure here is an average of loads on the left side of a vehicle: all the testers use the left side as the testing side due to easier driving as the driver sits on the left in a vehicle in Finland.

The base data in the load analysis included almost the same specimens in a similar way as in the above temperature analysis. The task force data and the comparison test data were analysed separately. In addition, the task force data was again divided into two parts depending on the type of the stone sample (see results in Figure 15) and the comparison test data depending on the tyre model (see results in Figure 16). The final road wear value in a test was inspected against the load on the left side of a vehicle in percentages of maximum allowed load for certain tyre. A few coarse errors were removed from the task force data.

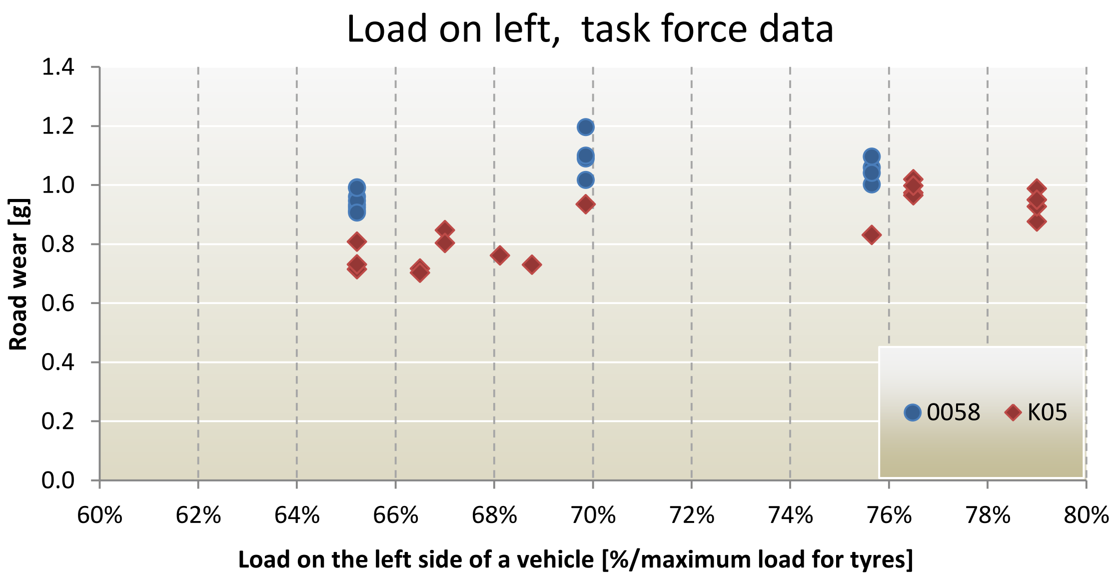



**Figure 15. Higher load (on the over-run side of a vehicle) seems to increase wear both with normal (0058) and K05 stones. (Task force, 2015)**

The graph based on the task force data seems promising and foreseeable. However, the trend according to the comparison test data is controversial indicating that an increase in load would decrease wear, on average. However, dispersion seems wide here, and the difference between minimum and maximum load is half of that in the task force data. Therefore, not as valuable conclusions can be made. The reason for these opposite deductions does not seem clear, but based on the physical phenomena, the task force data may follow the truth. At least three effects of increasing load can be considered: an increased footprint of a tyre which means greater angle of incidence of a stud to the track and an extended grinding time of a stud against the track. In addition, the stud force may increase, too, when the load is higher. Finally, wheel angles may change according to loads, which causes a slip angle on tyres: the wheel angles must be checked and adjusted, but if they are measured with a low load or no load at all, the difference in some type of suspensions may become significant – some 75% of the maximum load for tyres may mean the overall maximum for a vehicle.

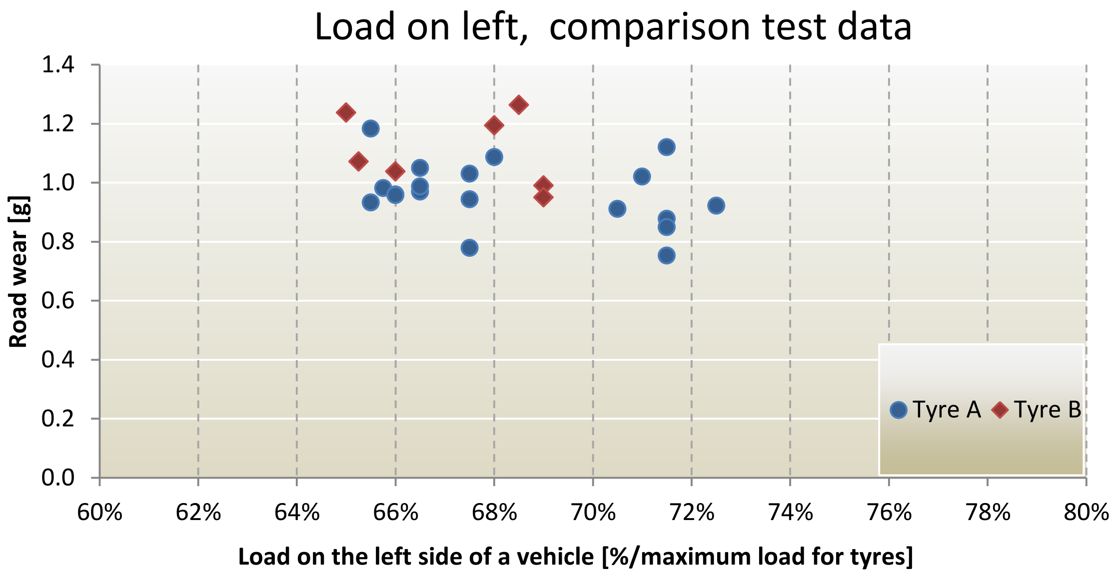



**Figure 16. The load seems to have had a slightly negative effect on wear on average in comparison tests with tyre A which is controversial compared to the task force data. (Trafi, 2014b)**

### 3.2.3 Stud protrusion

The test method description defines the limits for the stud protrusion: in the measurement before the testing, the average stud protrusion cannot differ from the value given by the manufacturer by more than 10% and the maximum/minimum stud protrusion of a single stud cannot differ by more than 30% from the average stud protrusion. In addition, the average stud protrusion at the end of the test – the change in the stud protrusion – cannot differ from the average protrusion measured at the beginning by more than 25%. In other words, studs need to be assembled onto a tyre according to the manufacturer's instructions – of uniform quality – and on the one hand, studs need to be tightly stuck on a tyre and on the other hand, the test needs to be driven gently enough in proper conditions.

A few hypotheses were raised up before the analysis, and the most important were evaluated to be the effects of the drive of a vehicle and the conditions on a track: is it dry or wet. Water works as "lubrication" between the tyre and the track so a wet track is evaluated to be gentler to the tyres. However, water also has cooling effect. Based on the literature survey and general understanding, larger stud protrusion was thought to lead to higher road wear. The information about the tests where both the conditions (dry or wet) and the change in stud protrusion were reported was narrow, but some less compelling conclusions following the hypothesis could be made as can be seen in Table 5.

Only a few data sets were available regarding each category, but when inspecting all the data together, a moderate number of specimens could be taken into account. The average values seem promising as each category's value itself, too. The large variation in figures reflects the random variation in the over-run test, and especially for a sensitive stud protrusion this variation seems natural, although the protrusion has even decreased in one category. It is notable that the way to measure stud protrusion may have varied between the testers so that the reported values may not be completely comparable with each other. The protrusion measuring demands a reliable and accurate method, and without that, the received values may vary within one tester, too. However, this result supports the hypothesis and, thus, seems feasible.

**Table 5. The low number of sufficient data samples weakens the reliability of this analysis, but it seems clear that stud protrusion increases a lot more when the test track is dry compared to a wet one. (Task force, 2015; Trafi, 2014b; Trafi, 2016b)**

| Changes in stud protrusion with regard to the conditions (dry/wet) | | |
|---|---|---|
| | Dry (no. of samples) | Wet (no. of samples) |
| *Task force data* | **47.8% (4)** | **12.2% (5)** |
| *Comparison test data* | **23.0% (3)** | **9.1% (11)** |
| *Type-approval data* | **16.6% (8)** | **-10.3% (3)** |
| *Weighted average* | **26.2% (15)** | **6.9% (19)** |

In addition to the track conditions, the drive of a test vehicle seemed to rise up as one variable that needs attention. The hypothesis was that stud protrusion does not change that much when testing with a 4WD vehicle due to more even share of traction and other forces for all tyres. The worst case considering the change in protrusion was thought to be an FWD vehicle. The analysis conducted based on all available data as one source proofs the hypothesis right as can be seen in Table 6: the protrusion change with a 4WD vehicle is lower than with an FWD vehicle on average. The RWD result is positioned between these two.

**Table 6. The result from the analysis concerning a drive of the vehicle follows the hypothesis although the dispersion is wide. (Task force, 2015; Trafi, 2014b; Trafi, 2016b)**

| Changes in stud protrusion with regard to a drive of a vehicle | | | |
|---|---|---|---|
| | FWD (no. of samples) | RWD (no. of samples) | 4WD (no. of samples) |
| *Task force data* | **15.3% (17)** | **-% (1)** | **-% (1)** |
| *Comparison test data* | **34.6% (7)** | **2.3% (4)** | **-1.5% (7)** |
| *Type-approval data* | **11.3% (14)** | **-% (1)** | **-% (0)** |
| *Weighted average* | **17.4% (38)** | **7.4% (6)** | **1.9% (8)** |

Considering the deeper effect of higher stud protrusion, the interesting question is whether it increases road wear or not. This information is widely available as the change in stud protrusion has for long been one of the figures that need to be reported. The analysis was conducted separately for each of the three different data category – the task force data, comparison test data and type-approval data. The stud protrusion was estimated to affect road wear in the over-run test based on a study conducted earlier (Unhola, 1995). However, studded tyres used in the research at that time were quite different compared to those used today. In general, studs were heavier, and also bigger protrusion was allowed. Nowadays differences between protrusions in different tyres are small, and that may be one reason why the dependency does not seem clear (see Figure 17). Confusion is also caused by the great variation of protrusions in a certain tyre model which, on the other hand, may indicate that the way for protrusion measurement differs between the testers.

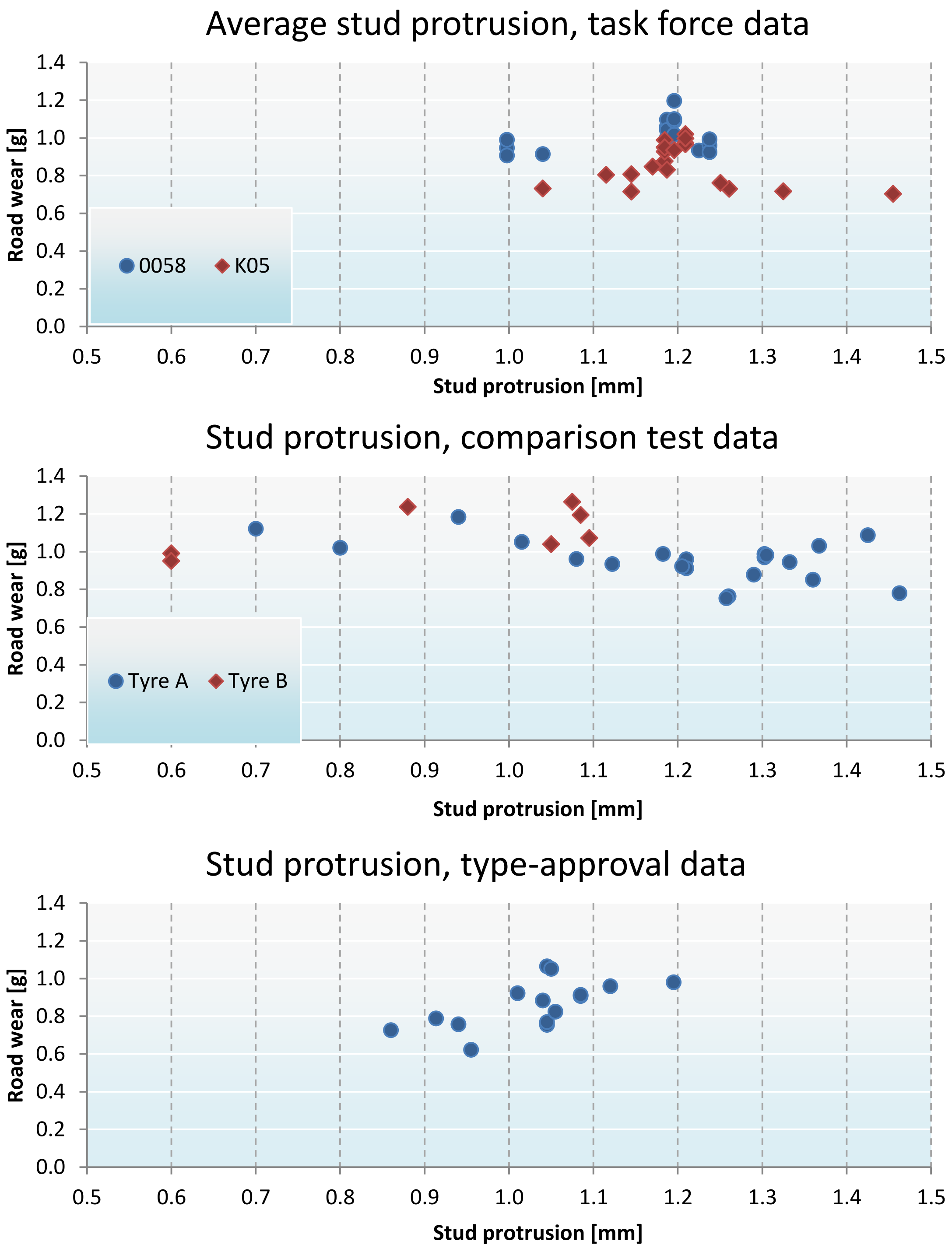



**Figure 17 a, b and c. Stud protrusion does not seem to have an effect on the result of the over-run test or it is more complex and does not show here (stud protrusion here is calculated as an average of average protrusions at the beginning and after the test). (Task force, 2015; Trafi, 2014b; Trafi, 2016b)**

This part of analysis can be concluded to be confusing as the results of the three different categories are all different. The type-approval data let it be understood that the hypothesis is true, but the task force data and comparison test data do not follow the assumption. Therefore, it can be concluded that a stud protrusion based on these data sets does not make any difference on the result of the test with regard to the tests performed with similar tyres. On the other hand, however, inspecting the type-approval data where all tyres are different, the trend can be detected. Thus, the stud protrusion increases road wear in general, but regarding one certain tyre, there are other properties that seem to define the road wear effect.

What is notable is that the traction force also has an effect on the wear. Thus, at least 4WD and 2WD vehicles should be set in divergent positions. An additional variable here is whether the vehicle is driven over the test stones with traction force or freely clutch disengaged or gear in neutral: this is something that has not been defined in the method description and, thus, it cannot be said whether the figures in the analysis are comparable or not. Nevertheless, Figure 18 follows the hypothesis. With regard to the task force data, the specific test where the same vehicle with similar tyres was used to compare the effect

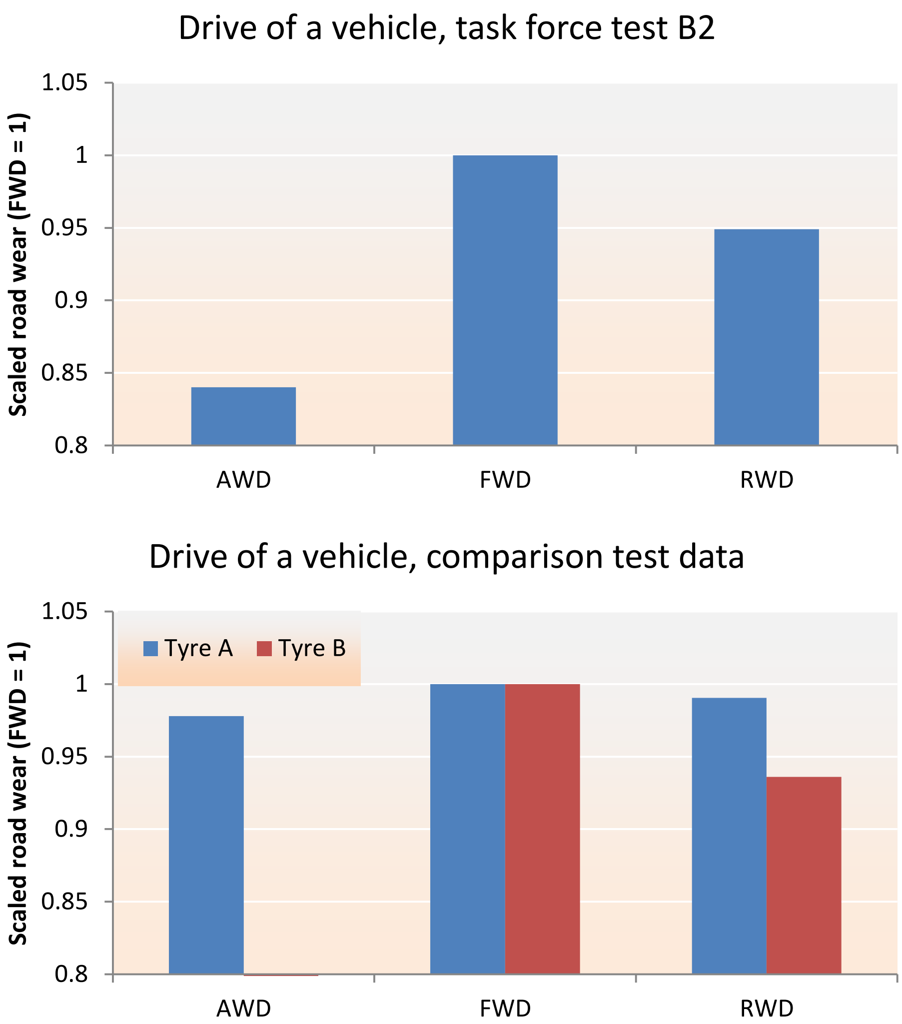



**Figure 18 a and b. The specific task force test for the drive of a vehicle and comparison test data (all data) follow the hypothesis. Road wears are scaled so that FWD = 1(g). (Task force, 2015; Trafi, 2014b)**

of the drive. The vehicle enabled switches from 4WD to both FWD and RWD. In addition to the task force data, the comparison test data was inspected in two parts depending on the tyre model.

The analysis of the stud protrusion’s effect on the road wear did not provide much results and the effect of a wet track could neither be confirmed. Figure 19 shows the controversial results of the different data categories.

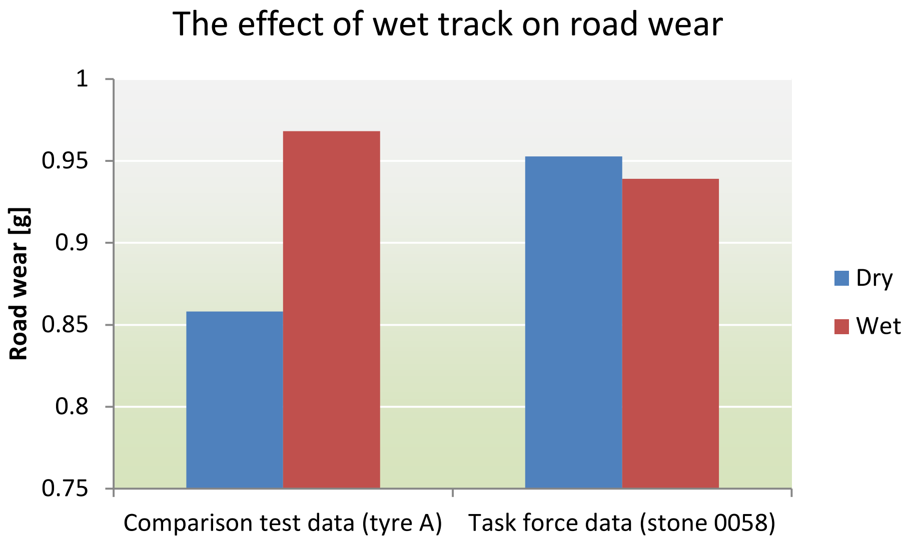



**Figure 19. The effect of wet or dry track on the road wear does not seem to be unambiguous based on the available data which was, though, narrow regarding this analysis. (Task force, 2015; Trafi, 2014b)**

Protrusions and changes in them during a test confirm an equal quality of tyres, studs and studding. Monitoring protrusions should not be given up in the future, but based on the available data, protrusions do not cause systematic errors in the test. For proving the hypothesis, a test where all other variables would be standardised should be conducted. This may be difficult as the protrusion can be considered a consequence of the tyre model and different tyres usually differ in other properties, too. Thus, special manufactured tyres would be needed for a detailed test.

### 3.2.4 Stud force

Stud forces are to be measured before the over-runs from 20 studs over the whole tyre tread and from both front and rear tyres. The legislation does not set any limits for the stud forces when using the over-run test method. In the traditional test method based on the different dimensions and properties of a tyre and studs, the stud forces are restricted: for a tyre of a passenger vehicle, the maximum limit is 120N (Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003). Based on the studies (e.g. Unhola, 1997), the stud force has been thought to have an increasing effect on wear, and that is also why the forces are inspected and regulated in the traditional approval method.

The data relating to the stud forces was evaluated in three parts separating the figures from the task force data, comparison test data and type-approval data. In addition, different tyres and stone samples that were used were inspected separately. The graphs are shown in Figure 20.

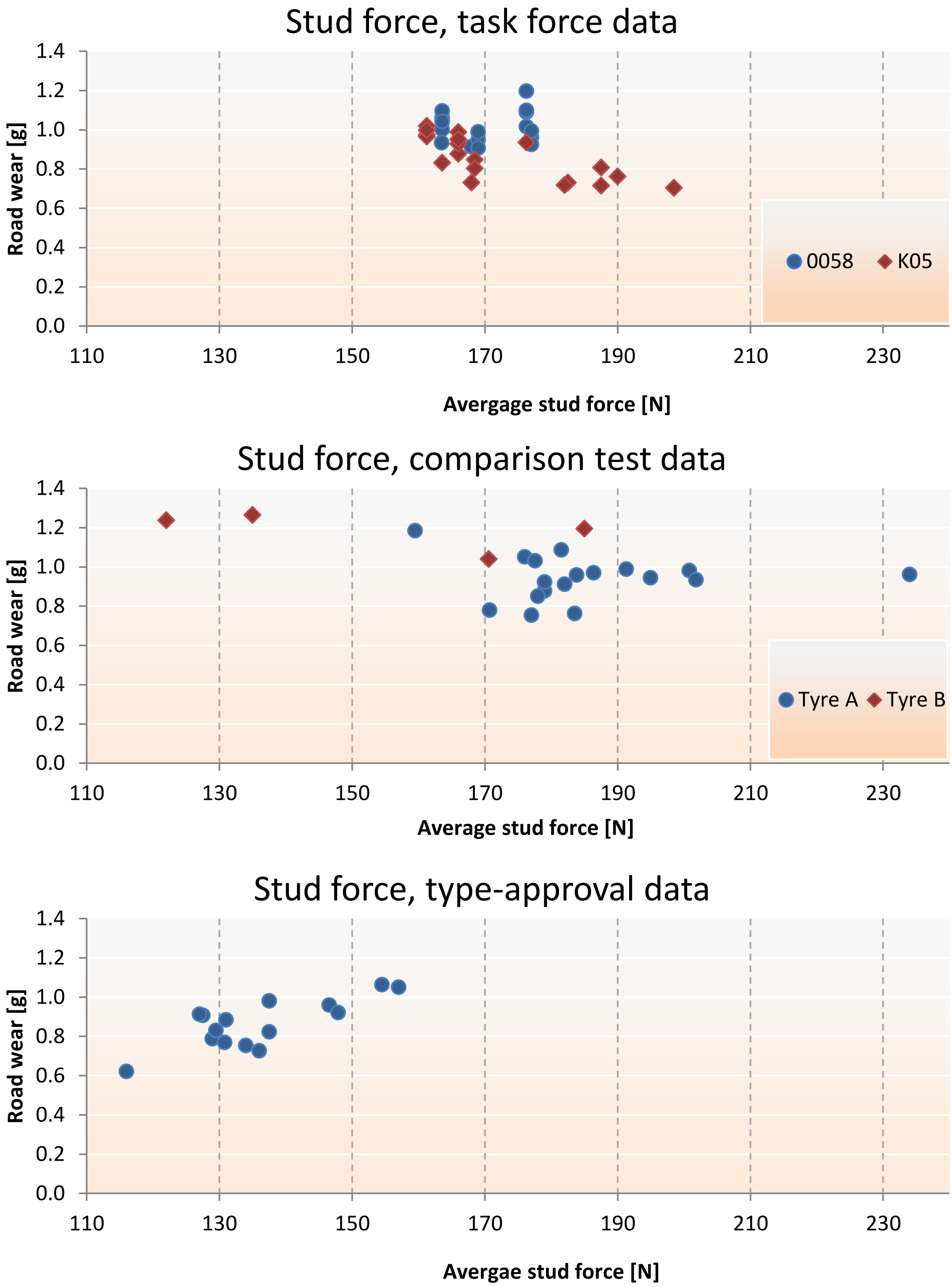



**Figure 20 a b and c. An increasing stud force seems to increase road wear based on the type-approval data that includes different tyres; the tests performed with similar tyres show that the stud force is not a determining variable. (Task force, 2015; Trafi, 2014b; Trafi, 2016b)**

The graphs differ from each other depending on the data category, and surprisingly, the wear values even seem to decrease when the stud force increases when comparing figures produced with similar tyres. Regarding the type-approval data, the trend seems to follow the hypothesis. Nevertheless, the result shown in the graph may not be considered valuable due to varying methods for the stud force measurement. The variation in the figures is, as it is in many other figures, too, large, and if the measurements have been performed differently, the trend seen here may not represent reality. However, assuming that the data is usable, it can be concluded that a higher stud force generally increases road wear. What is notable is that the effect is not the same with all tyres. When the average stud force varies within normal limits considering a specific tyre, the effect on the road wear can be either increasing, decreasing or it has no effect at all. This emphasise the idea of new technological development in the studded tyre industry as the results show that an increased stud force can be compensated by other properties. The idea supports the use of the over-run test as it shows that it is not necessary to regulate any strict limits for variables, such as stud force.

In general, it can be considered whether the static stud force directly affects road wear. The conventional stud force measurement, however, gives a possibility for market surveillance to inspect uniformity in quality, and therefore, it still is an important part of the method description – at least when it is done properly and in the same way everywhere. That seems to be a problem also with the stud forces, the range within a certain tyre is wide and, thus, it may be considered whether the force measurement has been done similarly in all the laboratories. This weakens the results shown above.

### 3.2.5 Test stone dimensions

The ever continuing issue in the over-run test is the low mass loss: 400 roll-overs result in only some 1 gram loss in five stone samples with today's studded tyres. One way to increase the wear within the same conditions is to consider changes in the stone sample. Most of the wearing is considered to take place on the edges and corners of the sample, so the task force has conducted a test where a few different stones have been compared. In addition to the changes in the dimensions, a change in material may result in a higher wear as a more radical development. This is not considered in this section, though, because such reference data was not available and the comparison of different material would need another study.

Another problem that has been considered over time is the cracking or cleaving of a stone sample on the edges and corners of the knobs. This has been thought to increase deviation when pieces come off in different sizes. Therefore, stone samples with shallower grooves were tested to figure out if the confidence interval would narrow.

The test was performed with three different stone samples in addition to the normal sample that is used in the over-run test. The first stone (K05) had the same dimensions as the normal stone except the depth of the groove that was 3mm instead of normal 5mm. Second, the knob layout was changed so that 56 knobs instead of the normal 36 were sawed on the stone with the same outside dimensions as the normal stone has (K03). Third, the smaller knobs were sawed again on the same size of stone so that the number of knobs was now 90 (K01). The figures are shown in Table 7. The data used for the analysis here is a part of the task force data and these types of tests have not been conducted earlier.

The stone type is thought to affect measured wear in the over-run test through three different mechanisms in addition to the earlier mentioned groove depth. First, the number of corners may be considered one of the most important factors as the corners are possibly the weakest part of the sample being in touch with the tyre and studs and, thus, being under load and impacts. Second, the total length of all edges of the knobs seems also meaningful: studs are more likely to hit near to the edges than corners, and since a stud's position is changed in relation to the track during the road contact, much material is presumably worn from the edges that are weak, too. In other words, in addition to the first impact, a stud sliding against a track during a contact over the knob edges may cause notable wear. Third, the knob area – the area where studs can hit – is considered as one possible variable, too. However, the preliminary assumption was that it is not the area that has the biggest impact: grinding and compression are thought to be minor parts of wearing in the over-run test.

**Table 7. Three divergent stone samples and the normal stone (0058) differ from each other in the knob dimensions but not in outside dimensions. (Task force, 2015)**

| Stone code | No. of knobs | Total edge length [mm] | No. of corners | Groove depth [mm] | Groove width [mm] | Knob area [mm$^2$] |
|---|---|---|---|---|---|---|
| 0058 | *36* | *1,274* | *144* | *5* | *5* | *2,812* |
| K05 | *36* | *1,274* | *144* | *3* | *5* | *2,812* |
| K03 | *56* | *1,680* | *224* | *3* | *3.75* | *3,150* |
| K01 | *90* | *1,800* | *360* | *3* | *3.75* | *2,250* |

The hypothesis can mainly be proved: deeper grooves result in higher wear and deviation as can be seen in Figure 21, and a higher number of smaller knobs seem to result in an increased wear (see Figure 22). As can be seen in Table 7, both the edge length and the number of corners decrease when the used stone type changes from K01 to K03 and K05. The knob area does not follow the same trend and it decreases from K03 and K05 to K01.

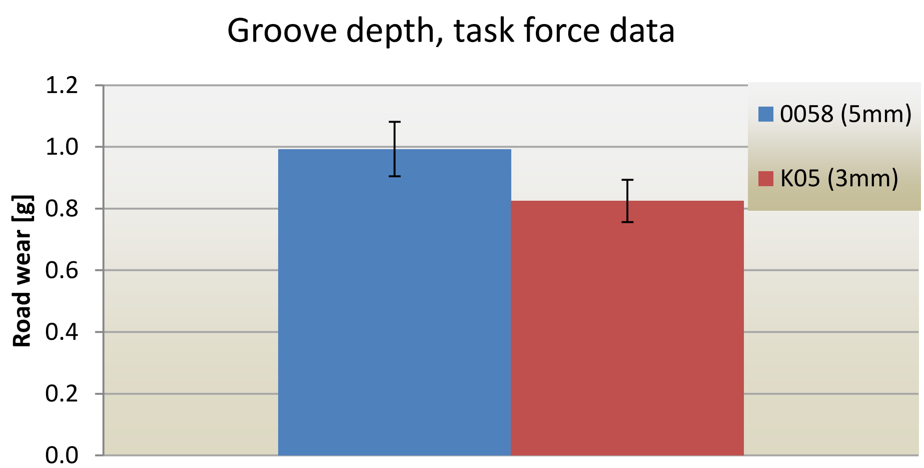



**Figure 21. The average wear with K05 stones (groove depth 3mm) is expectedly less than with the 0058 stones (groove depth 5mm). (Task force, 2015)**

Therefore, the hypothesis of the effect of the knob area can be dismissed. On the other hand, another assumption that the wearing mostly takes place on the edges and corners of knobs seems to be correct.

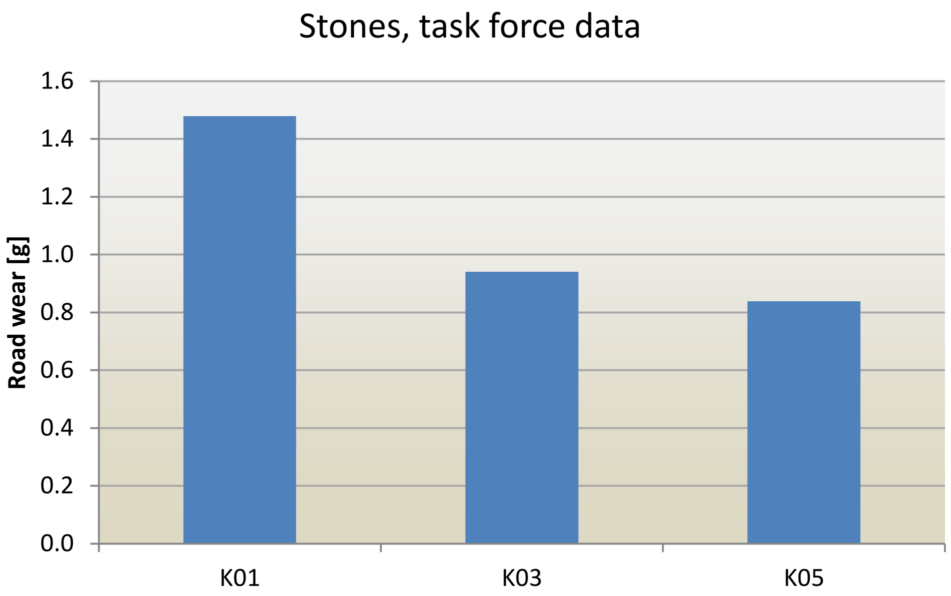



**Figure 22. The final road wear in the over-run test increases when the number of knobs of a stone sample is increased; the edges and corners of knobs wear most. (Task force, 2015)**

The graphs show a general trend: the edge length and the number of corners have a positive effect on wearing which was presumed. The depth hypothesis also seems to be proved at least according to this data. However, it must be mentioned that the data used here is very limited regarding the test stones K01 and K03 (four tests with both stones). Differences are, however, easily recognised and clear, so a general conclusion about these variables' effect can justifiably be done. Nevertheless, no accurate formulas or conclusions about each variable can be done, because all the variables change between different stones except the groove depth that is different only between stones 0058 and K05. Based on this data, one cannot say if it is the number of corners or edge length that causes the increased wear when comparing K03 and K01 stones, for instance. Each variable should be inspected somehow separately, but now all the variables change together towards the same direction regarding wear sensitivity – the knob area is an exemption as the area of K01 is the smallest. Multivariable regression analysis gives nothing relevant or trustworthy due to limited number of specimens. However, the general guidelines here are clear as the higher number of smaller knobs results in higher recognised mass loss in the stones.

Based on the figures, deeper grooves result not only in higher wear but also in higher deviation. Increased number of corners and longer edge length seem to have an increasing effect on wear, too, but without significant deterioration in deviation. The limited number of tests conducted with the K01 and K03 stones weakened the deviation study, though, and that is why it is not seen in Figure 22. It is difficult to say if it is the number of corners or the edge length that is more important based on the data. Nevertheless, they both are highly dependent on each other when the outside dimensions remain the same. However, what again seems to be clear, is that the knob area does not affect wear (see Figure 23).

Different graphic analyses regarding the effect of the presented dimensions of the stone sample may be done as can be seen in Figures 24, 25 and 26, too. When combining the groove depth and the number of corners (a product of them), a sufficient trend can be noticed. Nevertheless, there is no confidence that the figures would follow the trend if the test were conducted with stone samples with any other dimensions. The graphs, though, show the general trend with regard to these variables.

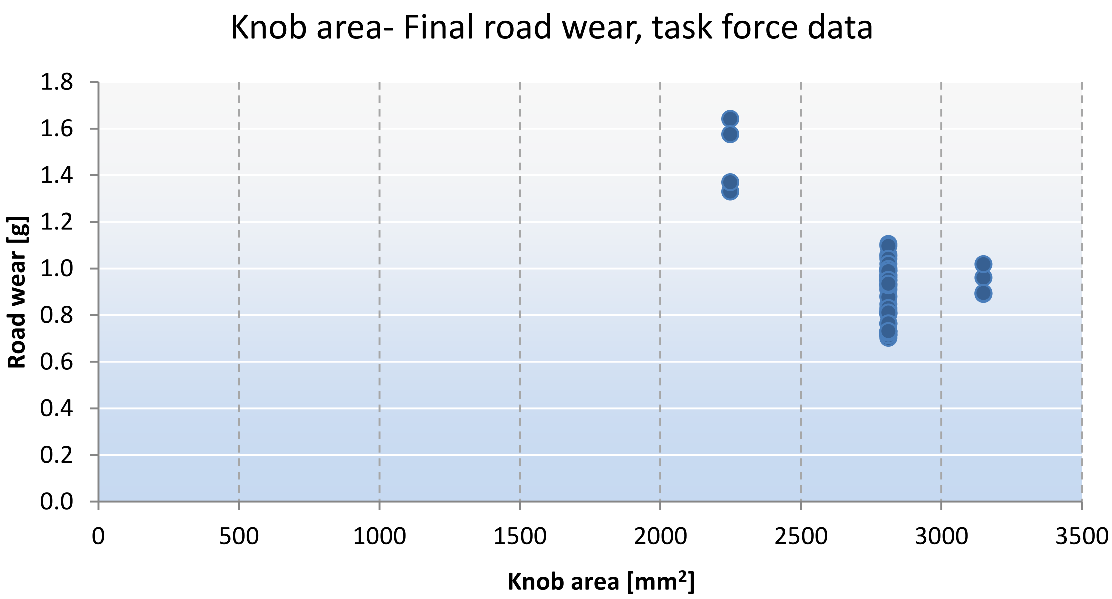



**Figure 23. The knob area does not show any dependency on wear result. (Task force, 2015)**

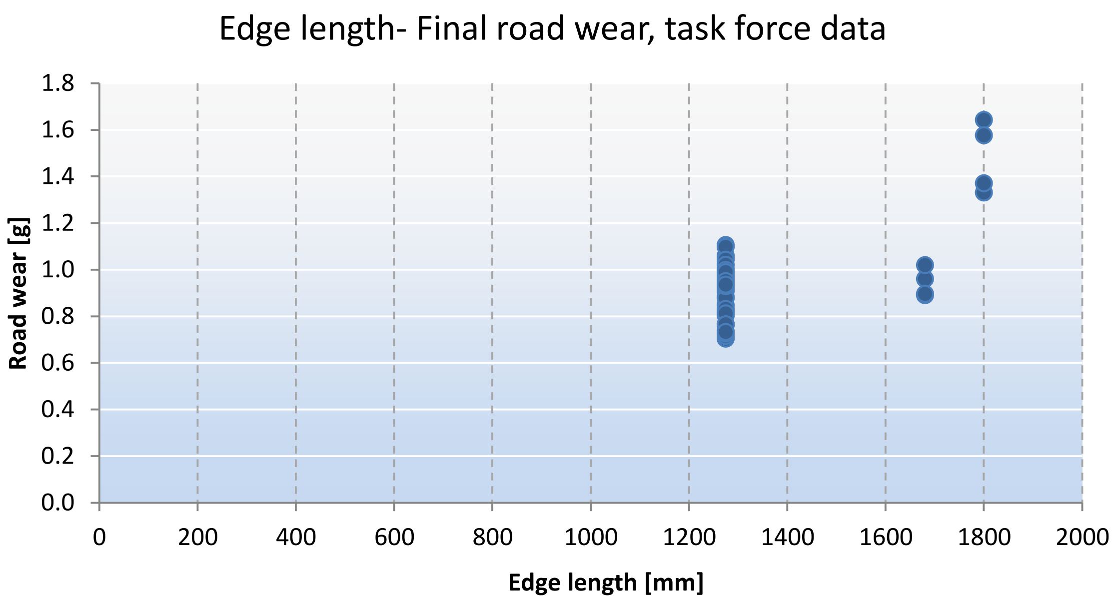



**Figure 24. The edge length alone shows a little bit of assumed dependency, but the trend is not clear not to mention linearity. (Task force, 2015)**

The deviation and confidence intervals in the tests conducted with different stones are important figures to inspect when considering whether this kind of stones could be used in the over-run test as a part of the type-approval procedure. The general goal of all parties is to get the wear to increase without increasing dispersion so that random variation that may compose a significant part of the final result at the moment would become statistically negligible.

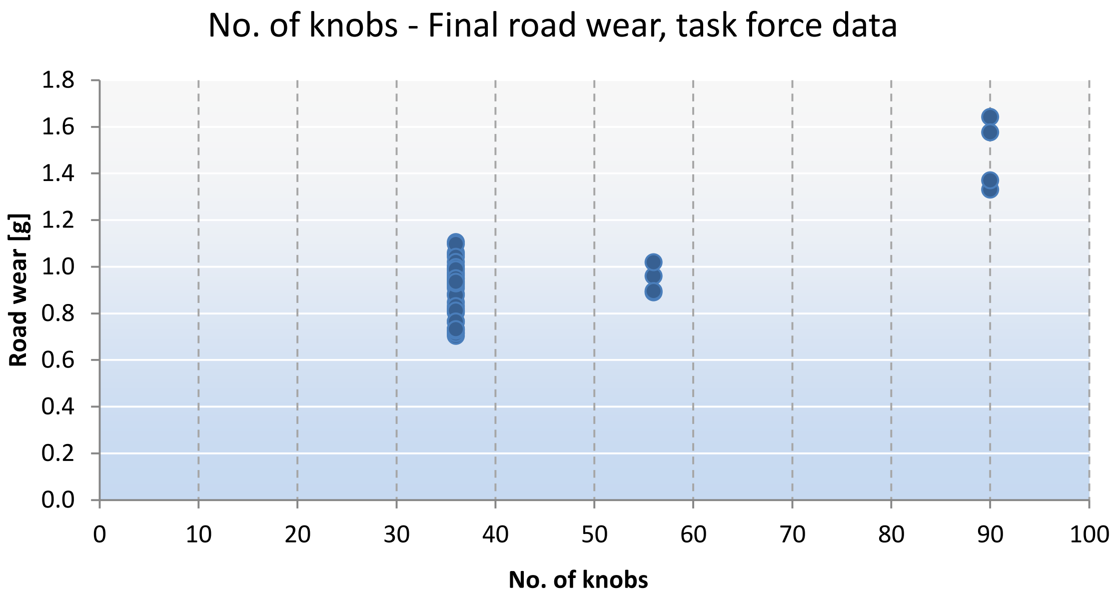



**Figure 25. The hypothesis seems to be proved considering the wear on the corners in addition to the wear on the edges of the knobs. (Task force, 2015)**

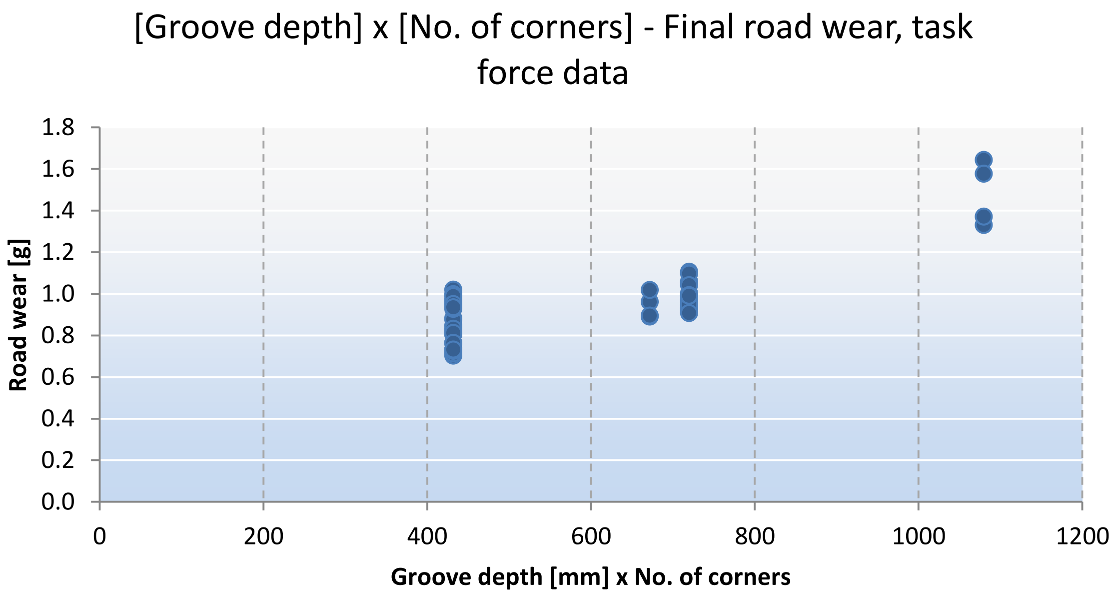



**Figure 26. Including groove depth in the analysis even better dependency is detected; dispersion is wide and the number of test with certain stones is low, though, and it is not justified to form any precise formula for the wear value. (Task force, 2015)**

### 3.2.6 Testing company

The primary objective of this paper has been to find systematic errors between the different testing companies (testers) performing the over-run test as part of the type-approval procedure. Therefore, differences under this heading are to be found. When inspecting these results and comparing the testers between each other, the difference between the errors occurred in these results and the errors that can occur within the test method description must be recognised. If the description lets a tester to perform the test in different ways, the situation from the authorities' point of view becomes problematic. This test data, however, may not reveal all the possibilities for differences, but only show those that may happen within unofficial agreements and general practice in addition to the official method description. According the understanding today, the good atmosphere among the testers motivates them all to develop the over-run test. Nonetheless, the situation may change, but the possible consequences and sources of errors regarding that are presented later. Only differences that have occurred in the tests that have been performed according to the current practice may be found.

Comparison between different testers is basically simple as the variable "tester" may have only five different values. However, problems arise due to many of the other variables that change from one test to another. The task force tests and comparison tests have been performed to try various different situations only to study the effects of variables on the wear – therefore, dispersion in those results may be larger than normally in the type-approval tests in which the conditions are probably more stable. In addition, with limited data, some other factors than the tester may have a greater effect on the final result.

The task force has tried to find differences with the help of specific comparison tests that have been performed just for inspecting tester specific trends. First, the tests have been performed with the same car with the same tyre model, but by different testers. In other words, the same vehicle went around all testing laboratories so that all variables other than the testing site and the operator would be as similar as possible. This data is produced by the task force, and the test is called B1. Thus, the difference – not the cause of the difference, though – has been raised up.

As a second specific task force test, the handling procedures of the stones have been under inspection: all the testers have performed the handling procedure before the actual over-runs, sent the stone samples to a certain tester who has carried out the driving and finally, the test samples have again been sent to the original laboratory which has again performed the handling procedure. The test conducted by the task force is called A3. This analysis has given some hints of causes, and concrete improvements have already been added to the test method description. The analysis work continues, though.

In addition to the comparison of the final test results, dispersion and confidence limits within the results of a specific tester are to be inspected. This analysis shows the repeatability within one operator but also tells about transferability within all testers. Primary reasons behind the possible issues with repeatability or transferability are not to be figured out within the analysis, but this brings up the differences and some hints of sources may be deducted. It must be noted, though, that this part only includes a few results per tester, so this is anything but statistically proved and random variation may be an interpretive matter here.

Some deductions can be done with the help of Figure 27 that presents the data from task force test B1. This includes two over-run tests per each tester. First, inspecting the reference corrections of each set, they seem to be really close to each other except for tester C who has smaller reference correction than others. However, both reference corrections of tester C, too, are close to each other, which means that the handling procedure is uniform from one test to another. The stones for both of the tests performed by the same tester have probably come from the same batch, so that the moisture levels and other properties have been as similar as possible. Thus, differences (that did not exist now) would have told about careless handling. Smaller reference correction of tester C seems reasonable compared to the other testers when inspecting the wear values: tester C has measured the lowest wear which means that final road wear values of all are close to each other.

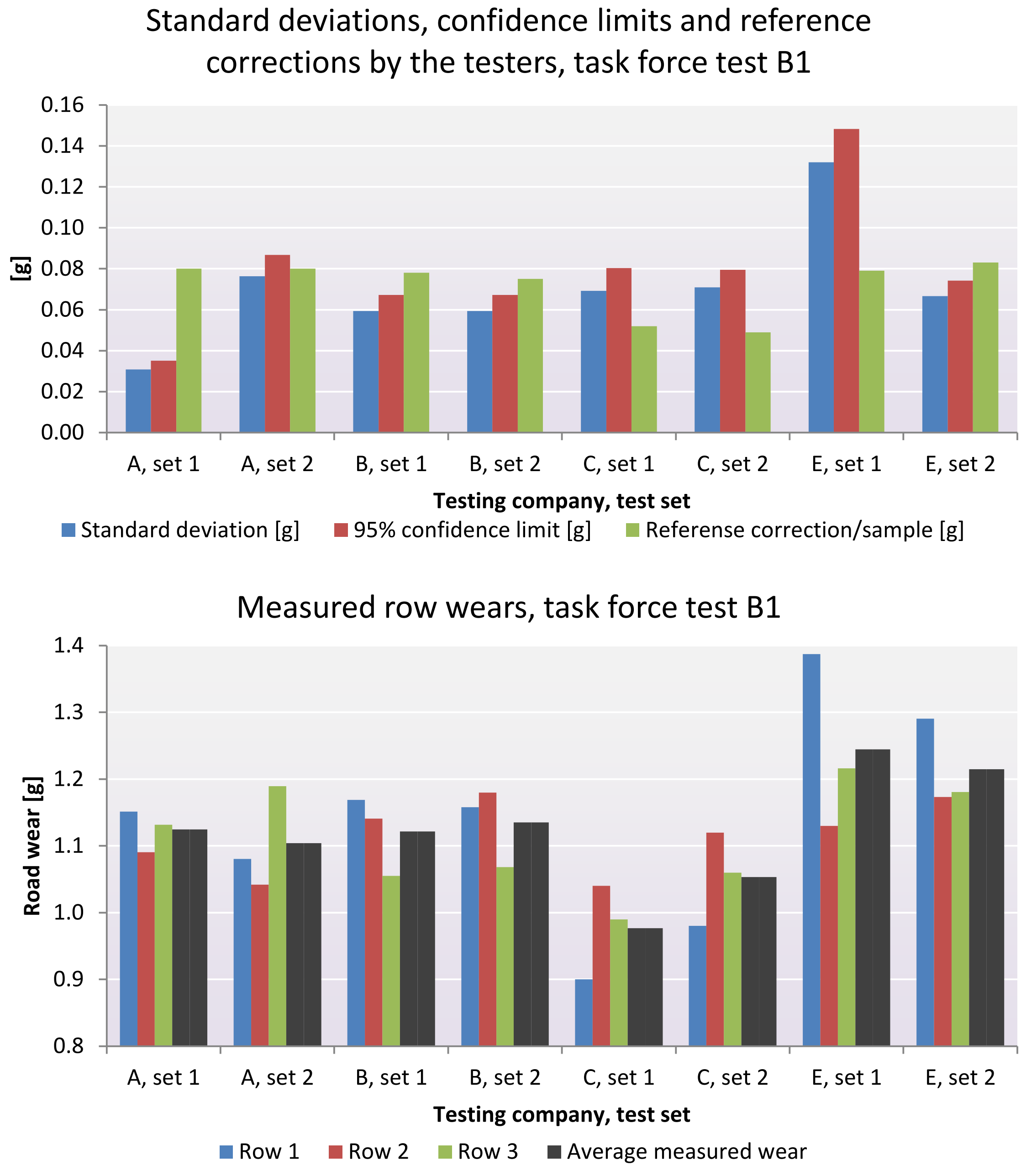



**Figure 27 a and b. Individual row wear values and confidence inspection show some trend within certain testers. (Task force, 2015)**

95% confidence limits are obviously following standard deviations in Figure 27. They are mainly in line with each other apart from tester A's set 1 and tester E's set 1. Most probably, these deviating values result from random variation that exists in the over-run test and tyre testing in general. Even though set 1 of tester E shows considerably large in the graph, that also fulfils the requirement of the test method description (15% confidence interval, 95% confidence). It can be considered whether the requirement for the confidence limit should be stricter than it is now because seven out of eight sets are now clearly less than the limit and as can be seen from the row wear values, the deviation regarding tester E's set 1 already seems large. On the other hand, it needs to give space for random variation that always exists in some scale. What is good, each of the testers managed to repeat the test with sufficiently similar results. Tester C got the most deviating results and the interval was 0.72–0.81g. Comparing the final results of all testers, the results were between 0.70–0.85g. This represents the current situation as the tests were performed in as similar conditions as possible and still this large variation existed.

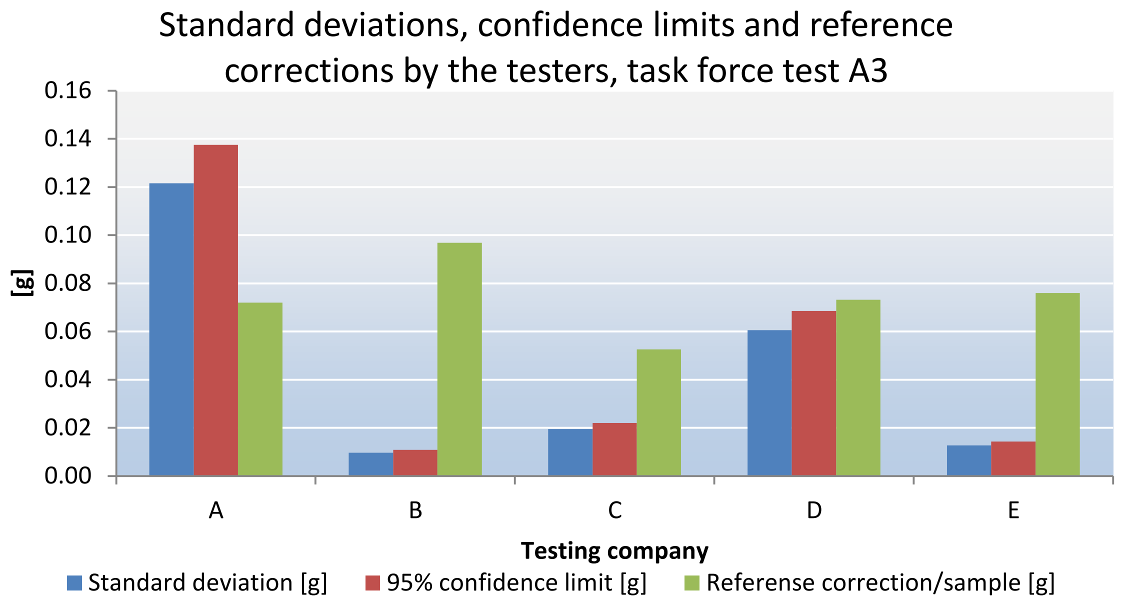
The difference between the maximum and minimum individual row wear value in this group is nearly 0.5g which may be considered large. Within one tester the differences are smaller but they still exist in considerable scale. Thus, the use of three rows in the test is more than justified, and it can be considered if even more rows should be used for better control of random variation. This would obviously mean more work for the testers and other means to achieve better result are primary. Anyway, using more rows would not remove the issue with transferability.

An interesting observation can be done when comparing the row wear values of each tester's two sets together. The row wear profile remains similar from set 1 to set 2. The clearest finding is seen with regard to tester E whose first row's wear is clearly the largest in both sets. If the first row wear were in line with the other row wears, the average road wear of tester E would also be close to the average row wear of the other testers. Anyway, this phenomenon seems to be caused by the setting of stones in a frame or the positioning of the frame on a track. Not all of the testers were using uniform frames for the test stones at that time which may be one reason for this. Today, every tester uses – as far as is known – a similar frame that is filled with the stones already at a laboratory. Thus, test B1 presented here would need to be repeated to get a confirmation for the assumption that a similar frame erases these kinds of differences.

In addition to the frame's position with regard to the track around it, the uneven profile of the track even much before the place of the over-run stones and their frame may cause a vehicle or tyres to oscillate so that the force of a wheel toward a track does not keep constant and either higher or lower load from a tyre to a track is applied when tyres cross the stones. This may cause more likely differences in the overall level of the wear, not differences between individual rows.

Another specific test round conducted by the task force (A3) aimed to find out differences caused by the handling procedure including washing, drying, cooling, weighing and everything that happens between these steps. The driving itself, the over-runs, was performed by the same tester at the same track at the same time (several consecutive stone frames on the track) so that any environmental variables could be avoided in this part of the procedure. The results out of this test round are presented in Figure 28 in a similar form as earlier in Figure 27. The individual road wear values, reference corrections and deviation within a certain tester are inspected. Another analysis regarding the handling procedure is presented in the next chapter.

Standard deviation and thus, also 95% confidence limits vary the most when comparing the testers with each other in Figure 28. While testers B, C and E are on an excellent level, tester D reaches acceptable deviation but tester A's value may be considered too large. The situation with tester A may be a failure during the over-runs or mishandling with the stones. If no error has occurred during the over-run phase, something must have gone wrong in the laboratory. However, no other analysis shows an exceptionally large deviation in the results of the same laboratory, so possibly this is caused by random error. If it is a question of contingency, the issue of the over-run test regarding low masses that are measured becomes concrete in these results. Such deviation in grams would not be a problem if the final wear value were greater on average.



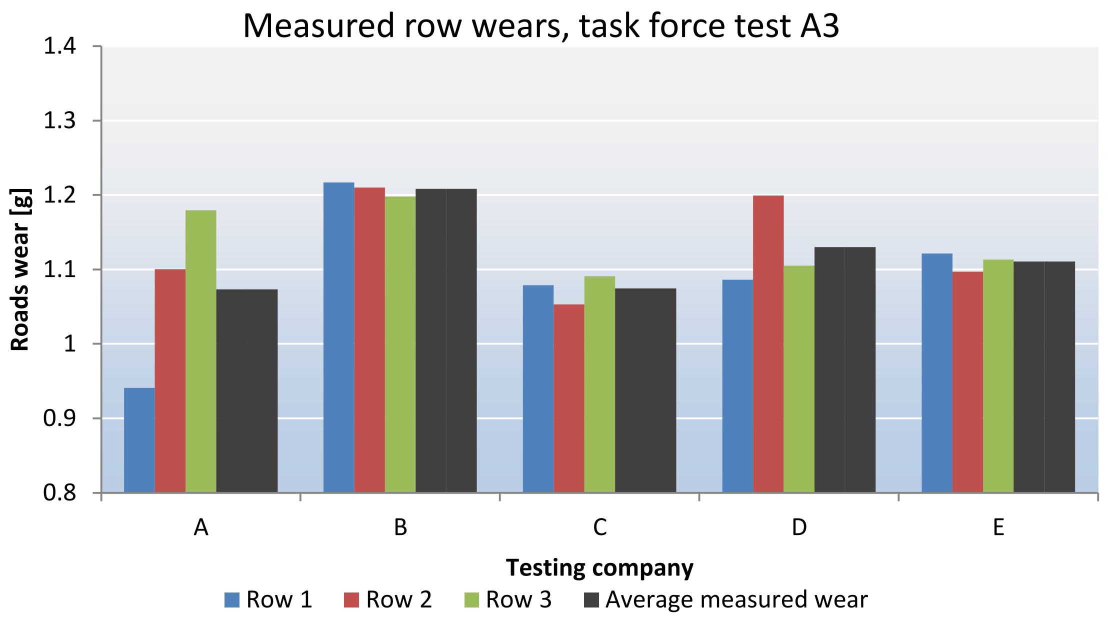




**Figure 28 a and b. In addition to the relatively large deviation within tester A, the reference corrections of each tester are at the maximum limit and partly exceed that. (Task force, 2015)**

Another observation concerns the reference corrections: only tester C's correction is clearly below the limit that would be 0.075g with a stone weight of 300g. Tester B exceeds that limit and the others are close to that. Means to lower the reference correction justifiably and reasonably would be something to figure out. Using the reference correction is anything but unambiguous or straightforward, which can be seen later in chapter 3.3.1. The reference correction composes a major part of the final wear value, which means that an error in correction composes a large error in the final result, too.

Testers B, C and E have reached a good coherence in the row wears that is enabled by both successful over-runs and successful handling procedures. Tester B has, though, clearly larger row wears on average, which may be caused by a different state of moisture of the stones at the beginning of the test. Larger reference correction supports this conception. Tester B's final result is actually some 0.1g less than tester C's.

In addition to the two earlier presented, specific test rounds B1 and A3, a broader view of the trends in the over-run testing was created by analysing a larger amount of data. The task force data was utilised regarding the tests conducted with stone K05 and the comparison test data by dividing the figures into two based on a used tyre. Thus, three comparable diagrams could be produced. With regard to the confidence analysis, the variation ranges as an average of 95% confidence limits of all individual tests were added to the graph in Figure 29.

Considering the aim of the thesis, it would have been valuable to find out if a certain tester always produces the greatest or lowest result of the over-run test and why. Tester E seems to have the greatest value in the comparison tests conducted in 2013-2014, but it settles in the middle of the range when inspecting the task force tests. On the other hand, tester D's final results in the comparison tests are almost lowest whereas in the task force tests it has produced clearly the largest wear. The most stable tester seems to be tester C when looking at all results shown in Figure 29. Otherwise it seems that the systematic errors that are looked for do not occur "systematically" when it comes to the testers. It needs to be noted that improvements and stricter limits were added into the test method description between the comparison tests and task force tests. That has changed the testers' procedures: some of them may have changed the practices more or toward another direction than some others so that the figures from the comparison tests are different from the figures from the task force tests. A test round similar to this should be performed as a continuation so that tester specific trends would rise up. The confidence limits in Figure 29 do not follow any systematic trend, which means that it may be random variation that mainly causes errors within every tester, and none of the testers produces the greatest or lowest dispersion every time.

With regard to the improvements implemented between the test series, a desirable result would have been to reduce both the differences between the testers and variation within each tester itself. Based on Figure 29, none of these effects can be seen, though. The confidence limits are large in all data, but, nevertheless, all the results of the testers do not fit in between these limits. However, testers' confidence limits are not considered critical, but the variation between testers is. Nevertheless, if some improvements to the test method are done, they will also reduce the testers' confidence limits.

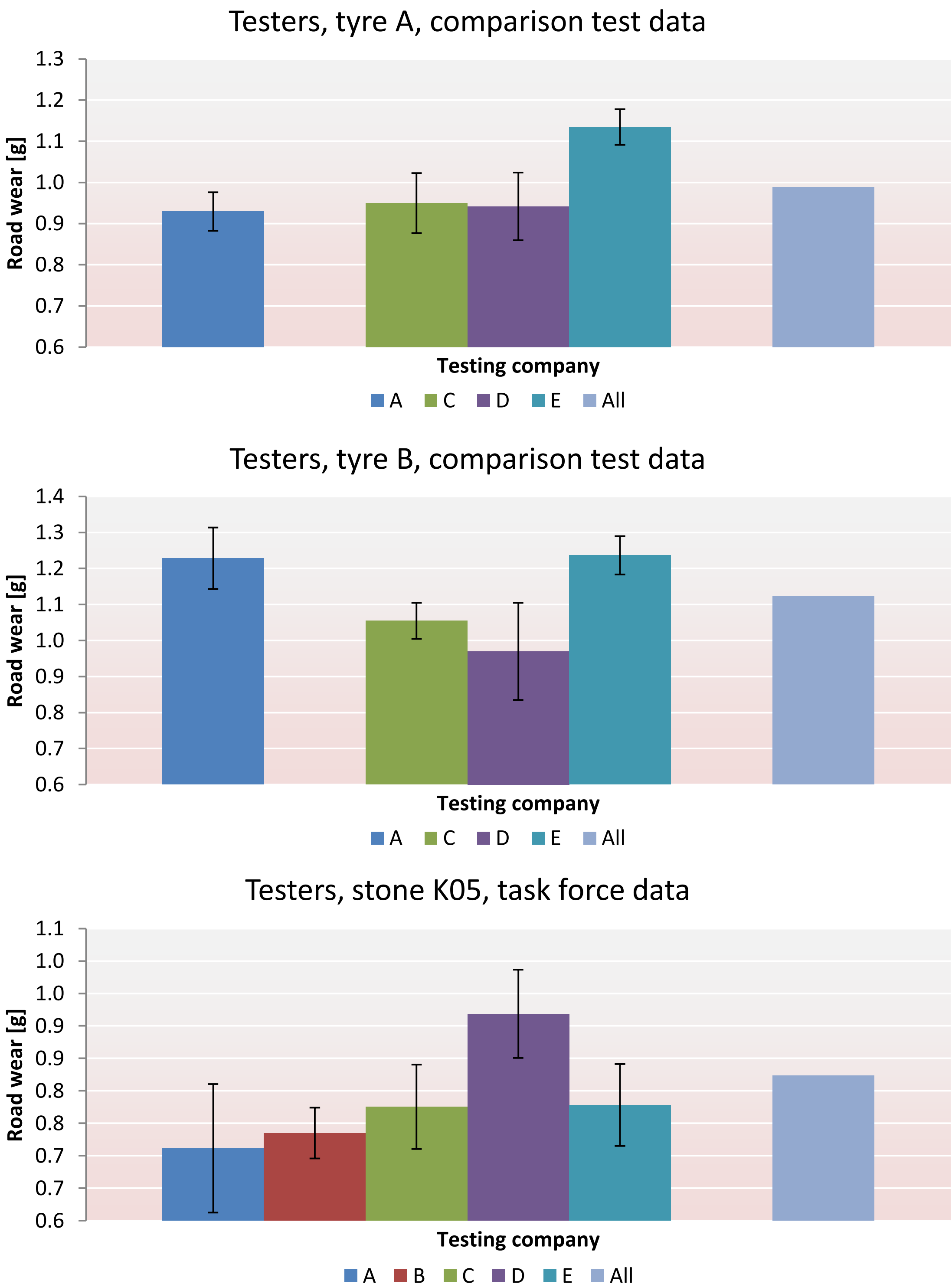



**Figure 29 a, b and c. The average of the final road wear values of tester D produced with stone K05 deviates from the others' averages; the variation ranges shown are the average of 95% confidence limits of the individual tests conducted by each tester itself. Tester B was not involved in the comparison tests. (Task force, 2015; Trafi, 2014b)**

Finally, another analysis of confidence limits of all testers regarding all tests they have conducted was performed. Now the confidence limit values were calculated based on all test results that were available within a certain test category (task force data/stone K05, for instance). This analysis tells how well the test method description of Trafi and, on the other hand, the description and procedures of each tester itself succeed to define uniform conditions and procedures for testing. In other words, the values in Table 8 include all allowed dispersion (temperature changes, drive of a vehicle et cetera), and it does not show the ability of a tester to repeat the test in the same conditions (repeatability) but more likely it tells how well a test can be reproduced within the testers' limits for conditions.

**Table 8. Confidence limits based on all individual row wear values within each category tell about overall testing conditions of the testers. (Task force, 2015; Trafi, 2014b)**

| 95% confidence limits of all row wear values [%] | | | | | |
|---|---|---|---|---|---|
| Tester | Task force data | | Comparison test data | | Weighted average |
| | K05 | 0058 | tyre A | tyre B | |
| A | 6,5 % | - | 8,8 % | 5,3 % | 7,0 % |
| B | 3,1 % | - | - | - | 3,1 % |
| C | 4,6 % | 4,0 % | 3,9 % | 3,7 % | 4,0 % |
| D | 3,4 % | 3,4 % | 5,8 % | 9,1 % | 4,4 % |
| E | 6,0 % | - | 4,8 % | 4,3 % | 5,4 % |

When inspecting the figures in Table 8 in general, an evaluation of the tester specific procedures may be done: reaching a level of 5% in 95% confidence limit is to be considered sufficient, but exceeding that seems problematic not only regarding a tester but also – and especially – regarding the official test method description. If the description let these large differences to exist within one tester, it is difficult to justify a confidence limit or deviation within all the testers.

The figures seem sufficient in general and it can be said that reproducibility within each tester is mainly good. Some exemptions exist, though. Individual larger values, such as tester D/tyre B, may exist due to random variation as the number of tests in some sections may be small. The average value in the right column is the weighted average taking into account the number of the tests conducted within each category. The more even the figures are, the better the ability to conduct reproducible tests is. Here, though, the shown confidence limits may be greater in relation to the type-approval testing due to the test arrangements that have demanded a wide range of variation in different variables. This kind of figures could not be produced regarding the type-approval data because it could have been a tested tyre that makes the difference and not the conditions or procedures as the percentages have been calculated as a 95% confidence limit of all individual row wear values.

When comparing the confidence limits of the comparison test data from 2013-2014 and those of the task force data from 2015, the later produced task force figures are lower on average. Exemptions within the testers are C and E who already had a good value in confidence in 2013–2014. The overall average decreased, though. Between performing these tests, Trafi launched the "Appendix with more detail" (Trafi, 2014) to define the test method description more closely (see Appendix 1). Several additional requirements and stricter limits for variables were added to the procedure. With regard to Table 8, it seems that the additions had an effect on reproducibility. Therefore, these corrections can be considered as justified and reasonable based on this analysis.

### 3.2.7 Handling procedure

As mentioned earlier, a more detailed inspection of the handling procedures among the testers have been conducted. The weight of the stone is very sensitive to moisture, and it demands careful handling. Weight loss in the over-runs is minimal – less than 0.1% of the mass of the stone sample – so all other changes in mass compose a relatively large part of the final result if anything that should not happen, happens. In addition to the moisture level, also the smallest cracks from unwanted impacts, for instance, may cause a crucial weight loss.

The data about the handling procedures concerns the practices in washing, drying, cooling and weighing of the stone samples by every testing company. The mass of the stones has been measured between every step in the handling procedure that is performed every time before and after the over-runs. This procedure may have a major effect on the final result. As said, even the smallest mishandlings may cause an error in the result. The data as such is considered to be sufficient and comparable, but what affects these results is the moisture level of stones at the beginning. If stones are fresh, meaning that they have not been stored long, they likely include more water or moisture. The wetter the stone is, the more water is evaporated from it within a certain time. Thus, the moisture level at the beginning has an effect here, but it is something that cannot be involved in the analysis due to the lack of information and a lack of such measurement. The theoretical effect of different moistures is presented later in chapter 3.3.1, though.

As can be seen in Figure 30 and Figure 31, the differences in the handling between the laboratories are significant. First, the washing seems to cause a major difference at the beginning. This may be justified by the procedures in a stone delivery: in what condition they come and when the first measurement is done et cetera. However, large differences also occur later and the maximum final difference between the stone which lost most weight and the one which lost least weight is considerable. The difference in the entire cycle between the largest and smallest is some 0.25g. If excluding the washing phase, the maximum difference is some 0.2g. Here it is a question of a mass of one stone sample. In the over-run test five stones are used which means that this data gives a result showing that the handling can cause an up to 1.25g difference. This ruins the whole test as the limit values for road wear are 0.9g, 1.1g, 1.4g and 1.8g. It needs to be remembered that the data concerns stones that come straight from storage or deliverer. This procedure evens out the state of the stones: if the same procedure were repeated, the differences would probably be smaller due to more similar initial states. Nevertheless, these large differences mean that there are some differences between the handling procedures depending on whether the stones are in storage or somewhere else, or in the states of stones and more detailed inspection regarding the handling itself should be conducted.

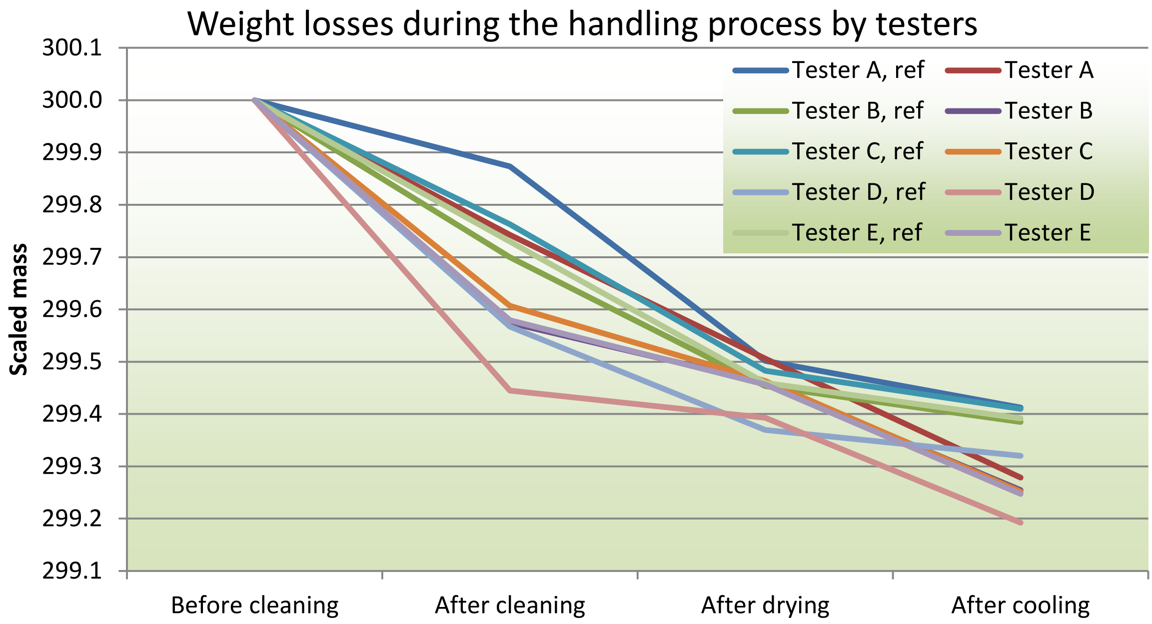



**Figure 30. Weight losses during the handling process before the test differ a lot from each other; this procedure is, though, to be done as a preparative work and "the weight at the beginning" in the over-run test procedure is to be measured not until the end of this procedure. Masses are averages of the masses of the individual stone samples (15 pieces of over-run stones and 5 pieces of reference stones) and they are scaled to begin from 300(g). (Task force, 2015)**

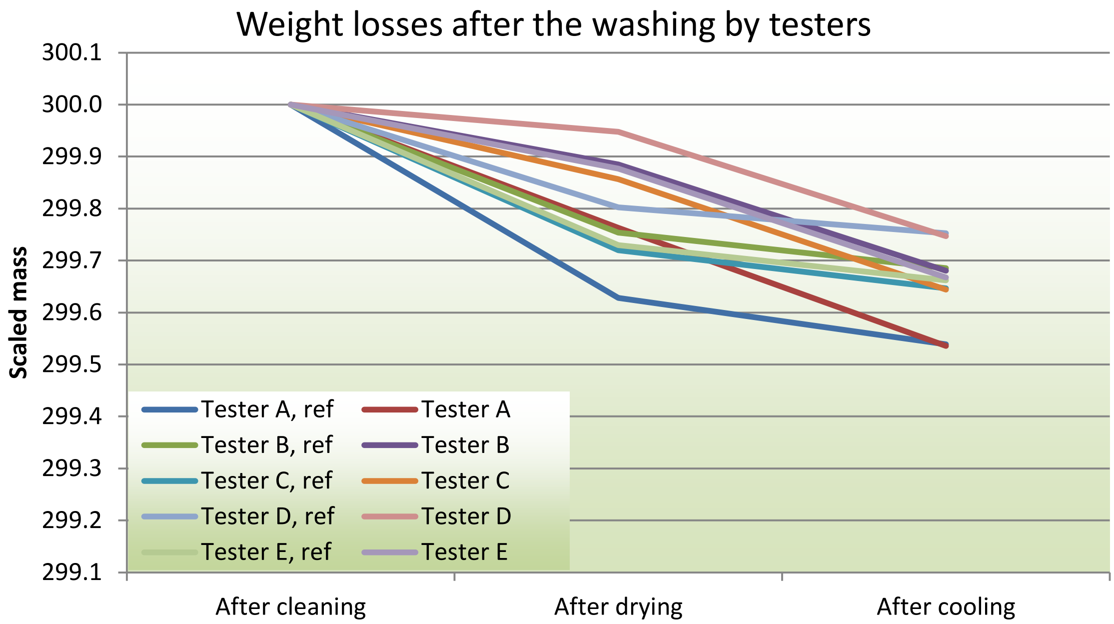



**Figure 31. This graph includes the same data as Figure 30, but the cleaning phase is ignored and the values are again scaled to begin from 300(g); the drying itself causes notably large differences. (Task force, 2015)**

### 3.2.8 Other

The hypotheses described earlier in this chapter were defined based on the preliminary analysis and assumptions about the most affecting variables in the over-run test. The test, however, includes dozens of variables like tyre testing in general, and the hypothesis chart could have been much extended compared to the current one. Here, only the most significant figures were introduced and analysed. If other variables in the test were to be studied, these more affecting variables should first be standardised so that smaller differences could be found. With regard to the reliability or transferability of the test, it may be assumed that the other variables would not have any significant effect on the results when the more affecting variables are eliminated. Thus, the other variables were not studied wider in this paper.

## *3.3 Theoretical analysis*

### 3.3.1 Moisture levels at the beginning

Moisture in a stone causes problems in the over-run test method as the moisture level of a test stone should be the same weighed at the beginning and at the end of the test to get a correct result of the measurement. Since no such meter with sufficient resolution has been in use and no other method to figure out a moisture level has been invented (usually the moisture differences are detected by the help of weighting, but now when the mass change is caused both by the moisture and over-runs, it cannot be separated the effect of these), the reference stones have been taken into the procedure as described before in chapter 2.3.2. A reference correction based on a change in the mass of the reference stones is meant to compensate any mass loss other than that caused by the over-runs in the real stones. The idea seems to be justified and it has been stated that the use of reference stones have been one of the major improvements in the test method during its lifetime (Unhola, 2015). However, in some conditions, the reference stones may enable even larger error in the final result than without a use of them – even if the moisture level would decrease in the real stones and thus, increase the “wear result”.

The problem with moisture and reference stones is related to the fact that the water in the stones evaporates differently depending on the initial moisture level. VTT has conducted a study ordered by Trafi that inspected the mass change of the over-run test stone samples over time (VTT, 2014). The research plan followed the procedure in the over-run test, and the stone weighing was performed between the cycles. First, the stones were washed, then dried for 72h in 110°C and finally cooled for 2h in a similar way than in the over-run test procedure. The first weighing was performed at this stage. Then the stones were kept under water for 3h representing the driving phase in the over-run test. After this, the same drying and cooling phases were repeated, and the second weighing was ready to be done. This cycle – 3h in water, 72h drying, 2h cooling and weighing – was performed three times in total. The averages of the weighing results are shown in Figure 32. Masses are scaled so that the first weight would be 300(g) sharp to clarify the differences.

The first thing to notice is that the mass decreases every time when the stones are dried. Thus, it seems that moisture come from a stone does not get back into it even if it is kept under water. The second observation reveals that the loss in the mass is smaller after each cycle. This is seen as an important matter regarding possible errors occurred with the reference stones. The graph clarifies that the moisture level over the over-run test cycle changes differently according to the initial moisture level or the state of the stone at the beginning. Nevertheless, it is stated in the study report that the mass loss during the cycle would presumably become negligible after approximately ten similar cycles.

The over-run test method description does not take a stand on “the state of a stone sample” at the beginning. It only defines the storage conditions, but with loose limits: stones must be stored in a warm and dry place (Trafi, 2014). In addition to this definition, no limits for the storing time have been set. Thus, the stones kept in a warm, well ventilated and dry storage over a winter surely are drier than those that come straight from an excavation and stoneworks. According to the nature of the test and general willingness, all stones would certainly be chosen from the same batch to eliminate this source of variation, but after all, the official method description does not demand this and therefore, enables choosing the reference and over-run stones from different batches or storing them in different conditions.

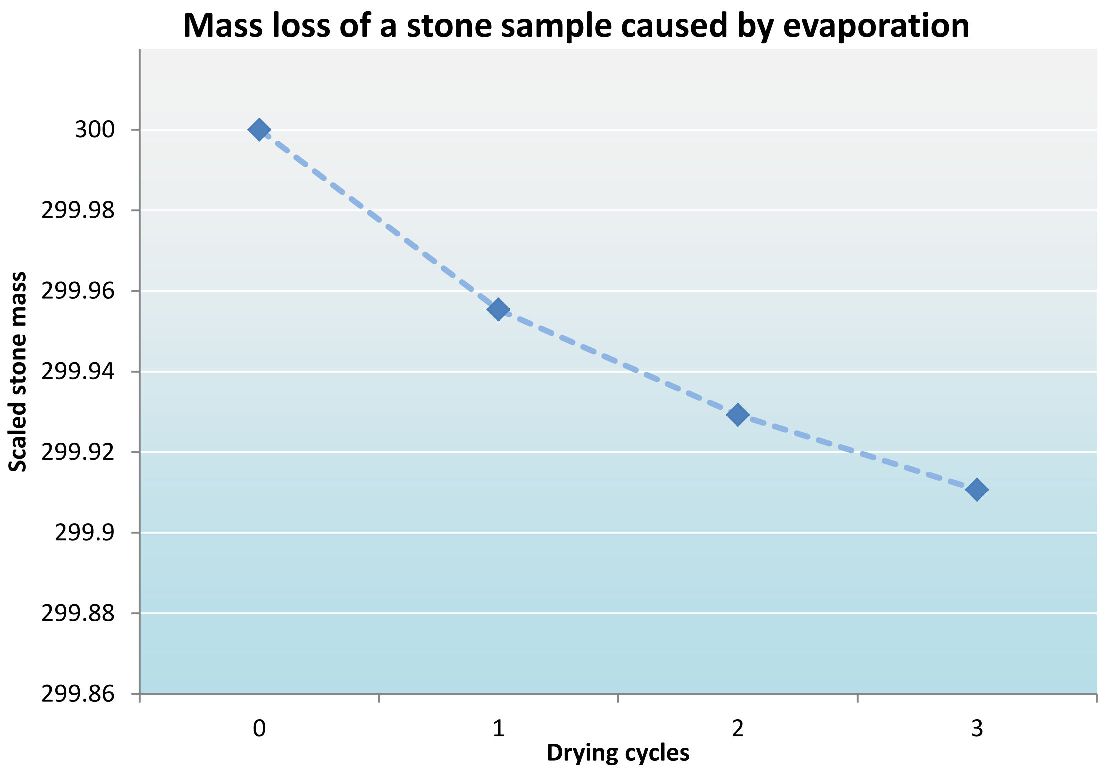



**Figure 32. The averages of stone masses after each drying cycle show that the moisture in a stone keeps evaporating from one cycle to another, but not linearly. (VTT, 2014)**

In Figure 33, a power trend curve is created following the weighing results that were presented above. The scenario in the graph is that the reference stones are picked from a fresh, moist batch and a mass at stage 0 represents this. On the other hand, the over-run stones come from a drier batch that has been stored for a longer time in a warm and dry place, for instance, represented by stage 4 according to the trend line. After one cycle – the over-run test – the mass of one reference stone has decreased 0.045g and the mass of one over-run stone 0.015g, considering just moisture. This means that one reference stone results in a 0.03g incorrect reference correction to the measured road wear, and as the final road wear value is a mass loss of one row of stones, the additional incorrect reference correction would be 0.15g. This seems large as it composes some 8–17% of the limit value depending on the load index class.

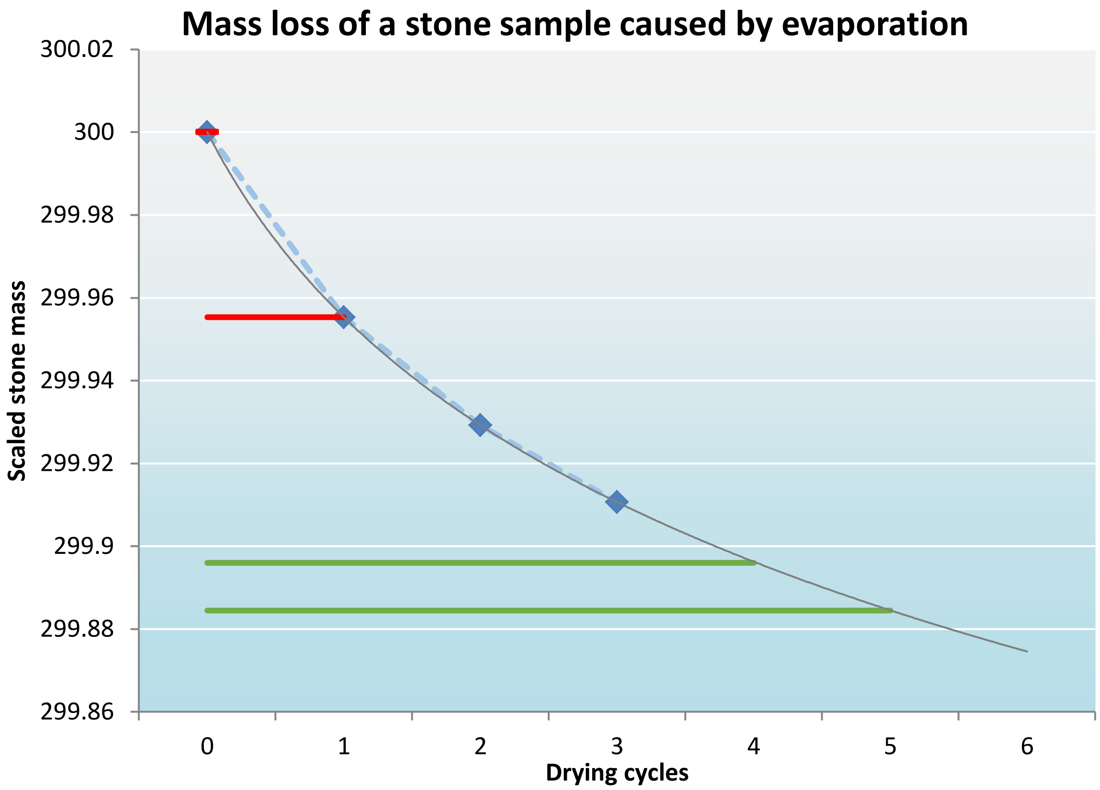



**Figure 33. The predictive trend line of drying cycles shows that a weight loss caused by evaporation during the over-run test differs depending on the state of moisture at the beginning.**

### 3.3.2 Variables affecting stud impact

Above in chapter 2.4.2, the wearing mechanism and the moment when a stud hits the road surface were discussed. As the impact is evaluated to compose a major part of wearing in the over-run test, the change in kinetic energy of a stud seems to represent the impact best. This energy is transformed to transformation of rubber or heat and damage of the stud and pavement. The energy can be calculated in theory, but a basic calculation does not give an answer to the question how much of it is fallen on the pavement. Dynamic stud force would be the most feasible variable here, but measuring it is anything but simple. Therefore, the method today demands only a measurement of static stud force. Static force, however, does not represent the correct situation as the force towards a stud – and, on the other, the force towards pavement – is not axial in relation to the stud. In addition, a stud on a tyre rolling at 100km/h is affected by several other dynamic forces.

One way to inspect the dynamic behaviour of a stud at the moment of impact is the angle of incidence. The idea behind this has already been shown in Figure 9 on page 35. The change in energy surely defines some part of wearing, but when the stud hits pavement, all other factors define how the energy is transformed and where to. For example, the already mentioned rubber behaviour in different temperatures, stud protrusion and the shape of the stud or a pin of it surely have an effect. Nevertheless, the possible factors affecting the stud impact are discussed here, and a much simplified calculation on the same matter is presented in Appendix 2.

A possible source of error may also be explained by means of the angle of incidence (see Figure 34): the angle may be different even with the same tyre depending on conditions within the official limits. In addition, the method enables the use of different tyre sizes with different load indexes for the testing in the same load index class, which makes even larger differences possible.

The tyre size was something that was difficult to analyse based on the test data that was received. Only two sizes of tyres were used in sizes closest to each other: other variables would have messed up the possible trend, especially when the division in the number of these was some 90/10%. Nonetheless, by calculation it is possible to evaluate the effect of different sizes to the final result. In the type-approval procedure, each tester has itself reported a few different tyre sizes in every load index class that are used. These follow the instructions given by Trafi. The test method description, however, does not strictly limit the size, and the division to the classes is done only according to the load indexes. The tyre size – here the outer diameter and the width – directly affect the angle of incidence and, therefore, presumably also road wear: the bigger the diameter, the smaller the angle and the wider tyre, the shorter the footprint and thus, the smaller the angle.

Another matter affecting the size of the footprint and thus, the angle of incidence, is the load for a tyre. The over-run test method description set requirements for loads, but the allowed load for one tyre can vary some 70kg in the middle load index class 600-800kg as can be deducted from the method description in Appendix 1. An even worse case is met if changes on load indexes (from 600 to 800kg) are taken into account, too.This causes a variation of some 15–20% in the total weight of a vehicle, which can be considered large. The heavier the load, the more a tyre is flattened and the greater the angle of incidence is.

Finally, the third component that has been considered here is the pressure of the tyre. The method description defines the pressure for each load index classes: for the inspected 600-800kg class it is 2.5bar. However, as it is well known, pressure follows changes in temperature whenever the volume stays the same according to the ideal gas law. Therefore, the temperature at which the pressure is measured, and changes in temperature inside the tyre during the test affect the pressure at which the test is driven. The method description only says that the pressure is to be measured from a cold tyre. Doing the measurement at 0°C, the pressure increases some 10% in a tyre if assuming that the temperature increases during the test to 25°C (10°C change in temperature results in some 0.1bar change in pressure).

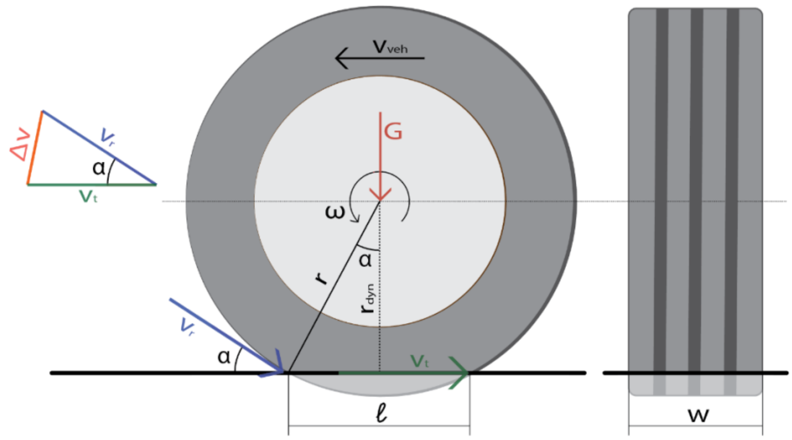



**Figure 34. The angle of incidence of a stud and the change in a stud velocity when hitting a road surface: see the calculation in Appendix 2.**

### 3.3.3 Internal reliability of the test

Even though it has been noticed that the over-run test includes several sources of variation, the test as a whole has been built to handle this variation and thus, produce realistic and correct results. Two methods for internal reliability have been included in the test. First, three consecutive rows of five stone samples are used instead of just one in order to eliminate random variation within the rows. Typical variation may be caused when a larger piece is cracked from one stone in a way that is not usual or realistic. By confidence limit analysis, this kind of false test is noticed and the test is to be conducted again. In other words, the wears of three rows cannot differ from each other too much.

Second, the two-phase way in which the test is passed prevents false approvals that may be possible due to random variation. The final wear value needs to be at least 10% less than the limit value to pass a test at the first round. This 10% margin is there for any unwanted but existing variation. If the result is less than the limit value but does not fulfil the requirement of the 10% margin, another test is to be conducted. This second test round defines if a test is passed or not: if the result of the second round is also less than the limit value, the test is passed. Calculation of probability of passing in different cases is presented below in Table 9.

The analysis of different scenarios in the over-run test within certain expectation values and standard deviations is based on a similar analysis conducted at Trafi (Rajamäki, 2014). The load index class 600–800kg has been taken under evaluation and probabilities of passing the test are calculated based on the following assumptions:

- an expectation value  is the “real” over-run test result that would be achieved as an average of infinite number of tests
- the measured results only include random variation that is normally distributed, and no systematic errors exist.

**Table 9. Expectation value in the table refers to the “real” road wear value of a tyre achieved as an average of infinite number of over-run tests; few tyres wearing too much do not pass the test whereas some of those that should pass the test, do not pass it. (Rajamäki, 2014)**

| Probability to pass the test in the load index class 600–800kg (limit value: 1,1g) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard deviation [g] | Expectation value [g] 0,9 | 0,95 | 1 | 1,05 | 1,1 | 1,15 | 1,2 | 1,25 | 1,3 |
| 0,03 | 100,0 % | 100,0 % | 99,9 % | 90,9 % | 25,0 % | 0,2 % | 0,0 % | 0,0 % | 0,0 % |
| 0,06 | 100,0 % | 99,3 % | 93,1 % | 67,7 % | 27,4 % | 4,6 % | 0,3 % | 0,0 % | 0,0 % |
| 0,065 | 99,9 % | 98,7 % | 91,1 % | 65,6 % | 28,1 % | 5,7 % | 0,5 % | 0,0 % | 0,0 % |
| 0,09 | 98,5 % | 94,1 % | 81,8 % | 58,9 % | 31,7 % | 11,8 % | 2,9 % | 0,5 % | 0,1 % |

The probabilities have been calculated with different values for standard deviation. The average of standard deviations of each of the tests (the task force, comparison test and type-approval data) analysed above is 0.065g which represents the current situation in the over-run testing. However, deviation depending on the tester exists, but it was not systematic as the tester with the largest/smallest result was different depending on test data. This tester-dependent variation is unwanted.

Based on the calculation in Table 9, the tyres that would wear the road more than what is allowed, are unlikely to pass the over-run test. For example, the probability to pass the test for a tyre with a “real” road wear value of 1.15g (limit 1.1g) is only 5.7% (with a standard deviation of 0.065g). On the other hand, the probability of not passing the test for a tyre that wears road 1.05g (limit 1.1g) in the over-run test is 34.4%. Therefore, it seems that it is more likely not to approve tyres that fulfil the requirements than to approve tyres that do not fulfil them. This can be considered favourable for the authority and the society.

In addition to the two-phase testing (if the result of the first test round is near the limit), the confidentiality examination regarding three consecutive stone rows improve the test method and compensate the random variation in the test. Random variation always exists in the field test and especially in tyre testing, but it is not considered critical based on the calculation and explanation above – standard deviation is still as low as some 6% of wear values, which is considered acceptable. Therefore, the improvements and development are to be concentrated in variation between testers also based on this section.

As a continuation to the previous analysis, it can be considered the sufficient level for the systematic error. The authority is, of course, interested in such definition because it has given a task to the working group (task force) to reduce the systematic errors: the extent of reduction, however, has not been defined. According to the task force test B1, where similar tyres were tested by each of the testing companies in a way that represents their normal conditions, the results varied between 0.98–1.24g and the average was 1.12g (see Figure 27 on page 59). Thus, compared to the average, the results varied more than ±10%.

As an example, it can be considered what the current situation with some ±10% systematic error is. It can be assumed that the random error is “evenly distributed” so that the ±10% variation is composed by the systematic error only. Therefore, the results vary in this range because of the testing company or other conditions only, not because of randomness in the results. If the “real” road wear value of a tyre were 1.0g in the load indexes 90–100 answering limit value 1.1g, the results in the best case with this ±10% systematic error would be 0.9g. On the other hand, the worst case would be 1.1g. This means that the tyre in certain conditions, in the best case, always passes the over-run test (probability 99.9% according to Table 9). In the worst case, the probability is only 28.1%. Comparing these probabilities, it seems to be certain that the systematic error has been too large. If the level of systematic error could be halved, the situation in the previous case would improve a lot: in the best case, the tyre would again pass the test nearly every time (probability 98.7%) whereas, in the worst case, the probability would more than double being now 65.6%, which can be considered feasible. Therefore, taking into account the nature of the field testing of tyres, the desirable level of systematic error would be some ±5%.

## 3.4 Qualitative analysis

Trafi as an authority has created frames for the over-run test by the test method description. This description, however, does not define the test procedure step by step, but only sets the limits for testing. For qualification as a recognised expert, every tester has needed to create their own procedure descriptions that often work as work instructions, too, for persons performing the actual testing. These descriptions vary from one another, and some testers have defined the procedures on a more detailed level whereas others have mainly followed Trafi’s paper. However, all of them have been recognised partly based on these documents, and it is interesting to compare things also on paper – inspections of the test procedure in every laboratory of recognised experts was not done within this thesis. Thus, possible differences on paper were important in order to find out the causes of systematic errors between the experts. However, testers possibly perform the test on a more detailed level than the instructions define so that all matters presented here do not necessarily follow the practice. This section of the thesis is written distantly to avoid issues with confidentiality of the work instructions. No companies are mentioned by name and no identifiable facts are brought up. However, the subjects where the searched causes may be found are presented.

The storing of the stone samples has been raised up as one possible cause of differences in the test results. According to the work instructions of the testers, only few require the use of over-run and reference stones from the same batch in one over-run test. Another matter is the storage conditions: both types of stones (over-run and reference) should be stored in the same conditions to confirm as realistic reference correction as possible. If the moisture level of both the over-run and the reference stones at the beginning and the end were uniform, the reference correction should be correct in theory. Some of the testers indicate that stone sets including both types of stones in right numbers go through the procedure always as complete from reception and qualification of stones. This kind of method seems feasible in accordance with the reliability.

Another slight difference that was noticed when comparing the description of each tester was the arrangement of the stones in the oven when drying them. One improvement that has been thought to cause differences in the evaporation process has already been performed: the oven must always be full of stones and if real testing stones are not used, free space in the oven must be filled with “dummy” stones so that the number of stones in the oven is always the same. However, the adjustment of stones in an oven differs as some of the testers set stones vertically whereas others set them horizontally. This might be a question of equipment, but a correction in the general description would be feasible, although the effect of this is not proved: such matter is seen as a minimal change in the procedure that is easily applied. As has been noted, the mass changes in the test are small and thus, when no information about the effect of this kind of matter is available, there is no reason not to define such a thing.

The thicknesses of the test stones is a critical dimension regarding the over-runs: the stones are worn unevenly if their heights differ from each other. As tolerances in the drawing of the stone sample enables variation of 2mm in height, the general practice has been to divide the stones before testing according to their heights into different groups. The maximum difference in one group is 0.5mm. However, all of the testers have not defined this procedure in their own work instructions, and thus, it is something that should be stated in the general over-run method description.

To keep moisture and impurities out of the test stones, their handling should be performed with care. Using clean gloves when handling the stones should be included in normal practice in laboratory conditions. Nevertheless, defining this in the description would let no doubt whether gloves are used or not.

Traditionally, the stones have been carried to a test track separately in a briefcase or similar, and they have been set into their frame at the track. Recently, the testers have taken mobile frame boxes in use: the stones can be set into the box already in a laboratory, and the whole set can then be transported to a track. This frame box includes holes for bolts, and attaching it onto a track is easy and fast. Although the practice is to handle stones carefully despite the condition et cetera, a question may be asked whether the stones are set into the frame as carefully on a track in cold rain, for instance, as in normal conditions in a laboratory. The setting in a laboratory unifies also this part of the procedure. The frame box used should also be defined to be the same to all testers. Hence, any cracks caused by careless handling may be avoided and the stone samples may be laid on a track in as similar way as possible despite the tester or the track.

The time in an exsiccator after the drying period is there for stabilising the state of the stones. Actually, they are nowadays using desiccators or similar instead of exsiccators – the idea is the same, though. However, the time that passes between the time when the stones are taken from the exsiccator to the time of weighing is rarely defined. Moisture in the air is sucked in a stone and, thus, it increases the mass of the stone whenever it meets normal air after the exsiccator. Procedures differ from each other as regards whether the hatch of the exsiccator is left open or not between several consecutive weightings, or no stand has been taken on it. Even small changes in moisture level may cause a critical change in the mass of a stone and thus, also reference correction. Moisture, which causes most of the difficulties in the procedure, should be controlled more carefully also in this phase.

When inspecting the driving part of the test, a crucial matter is assumed to be whether a vehicle is driven over the stones with traction or not. As has been mentioned, traction force has an effect on wear (Gültlinger, et al., 2014). Basically, the options here are to drive with constant speed with traction force applied, pull up a throttle so that engine braking is applied or disengage the clutch or change the gear to neutral so that the vehicle is rolled as freely as possible. The speculation of the effect of the drive of a vehicle tightly relates to this question if a vehicle is not rolled freely over the stones. Driving with constant speed and traction would reflect the reality best and increase the final wear, but it would put different drive types into divergent positions. In addition, a problem may arise due to a differential: the torque is split between wheels indeterminately, but on the other hand, driving to both directions may equalise the differences. Regarding 4WD vehicles, the way the torque is split between axles in the first place makes the situation even more ambiguous. Technology today enables quite many options between 2WD and 4WD. Anyway, the way to drive over the stones should be defined despite the drive of a vehicle.

In addition to the driving style over the stones, the style determines a lot also between the actual over-runs. The vehicle is accelerated to 100km/h only to be decelerated again to some 10–20km/h. Together with the 180° turnings between every over-run, the driving strains a vehicle and tyres quite a lot. Thus, it really matters if the accelerations and turnings are performed with care or not: humans can never conduct a test in exactly the same way especially when persons conducting the test in different companies have probably never seen each other's driving. The limit for acceleration is defined ($2m/s^2$), though. However, divergent driving styles are enabled also within this maximum limit. The predicted consequence of a harsh driving style is an increased stud protrusion – no major differences in protrusion changes between the testers could be proved based on the numerical analysis of test data, though. Anyway, a tyre and studs as a combination wear differently when driving differently, and a change in protrusion may not exist even though the characteristics of a tyre-stud combination would change.

With regard to the driving style, a difference may occur depending on the turning direction. Most commonly, a vehicle is turned left so that over-run tyres on the left side are on the lighter side of a vehicle and thus, less strained. Again, this is based on general practice but defining this in the method description would confirm a uniform situation in every test. What is notable, the aim to have an as small wear result as possible has driven testers toward a certain direction – to perform turning to the left. Therefore, the practice in general may be very uniform even though it has not been defined anywhere. However, regarding more complex matters, all the testers may not have found “the best practice” within the defined limits and thus, differences – systematic ones – may exist. The method description should be there to define all the necessary procedures.

The over-run stone samples compose less than 0.01% of the whole driving length in the test. Thus, the track surface outside the stones defines the conditions in the test. The method description only says that the track is not to be much rutted. A poor surface of asphalt may, though, affect the tyre and stud wearing during the test and, thus, affect the final result of the test. The stud protrusion measurement before and after the test – and the defined maximum change in stud protrusion – aim at controlling both the driving style and the conditions on a track. Nevertheless, the features of a tyre may change even though the protrusion would not change. A track in a harsh condition may wear the body of a stud or a pin of it differently or studs may be set onto a tyre differently as no running-in is applied and over-runs are the first driving for the tyres. Based on the analysis presented earlier, the stud protrusion does not alone define the wear result and many other things also have an impact.

# 4 Results and reflection

## 4.1 Description

The result section of the thesis is to present the answers for the research questions with the help of the analysis conducted in chapter 3. First, a quick summary of all the results achieved by the numerical and other analyses are presented, and a rough evaluation of the effects of each variable or phenomenon is made. In addition, the confidence of such evaluations is considered based on the clarity of the figures above. This chapter concludes all the valuable deductions that meet the aim of the paper. Possible improvements to the over-run test and the test method description are to be evaluated based on the conclusions below.

In addition to the summary of the analysis, the need for additional tests or research regarding the variables inspected here is stated. Chapter 4.3 includes some needs and ideas for concrete field tests that may either support the theoretical sections of the analysis or clarify the effects of uncertain variables.

The concrete improvements that are presented below are divided into three sections depending on their nature and on the fact how easy they are to apply. First, improvements that would be simple to apply into the current method description are listed. This mainly includes only additional corrections to the method description that would change nothing but the way to carry on the procedure. In other words, there is no reason not to define these improvements, and include them into the method description would not change the procedure as such. Thus, there would be no need to redefine the limit values, for instance.

The second part of the improvements includes more significant changes to the method requiring more time and preparation from the authority. These changes would surely demand new limit values for wear – for the result of the test. These improvements would change the nature of the over-run test more than it has been changed during its existence, and a thorough preparative work should be done before any enforcements. If these improvements were taken into use, a transition period should be provided to the manufacturers and testers of studs and tyres. The improvements are to be considered to be put into practice in the future over a longer time period. In addition, the thesis does not provide a complete proof for these changes and thus, additional tests concentrating on the variables or phenomena related to the improvements should be conducted.

Finally, in the third sections of the considered improvements, a more extensive idea about the development of road wear testing is considered. This includes long-term aims of the testing of studded tyres, and the over-run test as such is not included in this section. The improvement of the testing presented here is more likely only an idea and not precise or accurate action and its purpose is to show some guidelines for the tyre testing and development. The aim of this kind of improvements is to avoid the weaknesses that appear in the over-run testing.

The development ideas presented would change the type-approval procedure more or less depending on the type of change. Effects on the tyre and testing industry are considered and evaluated in the reflection part of the paper in chapter 4.6. Evaluation of the improvements as such is, however, presented in this chapter. The evaluation provides answers to the research questions that have been defined at the beginning of the thesis in chapter 1.2.

## 4.2 Summary of the analysis

A quick and compact summary of the analysis conducted in the previous chapters is presented here to clarify the variables and their effect on road wear (in the over-run test) and to compare them with each other. Table 10 concludes all the most important results and conclusions that were made based on the analysed data and it follows the hypothesis chart (see Table 4 on page 42). First, the confidence of each variable's or factor's effect is evaluated: the more marks are shown, the more certain is the presented consequence. Second, it is evaluated how large the effect of a certain variable would be in the over-run test.

**Table 10. The concluding chart shows the results of the analysis conducted earlier.**

| Variable/ factor | Effect on wear | | Description |
|---|---|---|---|
| | Confidence | Effect | |
| *Temperature* | ◆◆ | □□ | Higher temperature (air/track) results lower wear |
| *Load* | ◆ | □ | Results from different data sources showed controversial dependency, but it is assumed that a higher load results higher wear |
| *Drive* | ◆◆◆ | □□ | The drive of a vehicle affects both wear and change in stud protrusion; 4WD lowest, FWD highest, RWD in between |
| *Stud force* | ◆ | □ | Higher stud force results in higher wear on average, but with regard to a specific tyre it is not an interpretive variable |
| *Stud protrusion* | ◆ | □ | Higher stud protrusion results in higher wear on average, but with regard to a specific tyre it is not an interpretive variable |
| *Stone sample* | ◆◆ | □□□ | More knobs, longer edge length and deeper grooves result in higher wear. |
| *Testing company* | ◆ | □□ | Differences between testers exist but they do not correspond when comparing results from different categories. |
| *The state of the stone samples at the beginning* | ◆◆◆ | □□ | The method description let this error happen – and the error is clear – but it is uncertain how the testers benefit or suffer from the initial state of the stones. |
| *Weighting procedure* | ◆◆ | □ | The procedures of the testers differ from each other, and a clear error may occur – the significance of this is uncertain as such detailed data was not available. |
| *The range between the limits for certain variables* | ◆ | □□ | Tyre pressure, size and load of a vehicle can vary within the limits and the overall effect may be considerable based on theoretical calculation. The effect in practice should be studied. |

The statistical analysis composed a significant part of the thesis, and it gave a few dependencies regarding variables and their effect on wear. In addition, some factors were detected that do not affect wear or at least, the effects are not interpretive. Dozens of dependencies were studied before it was decided to show the presented variables in this thesis, but also the presented variables and factors include uncertainty due to large dispersion, incoherent data and controversial results from different data categories. However, the conclusion based on this kind of unclear data may be made in some cases: the studied variable is not interpretive. On the other hand, by this analysis and the sections that did not give a clear result, guidelines for further study have been created.

The first conclusion based on the analysis is that the traditional limits for physical measures of studs and their setting on a tyre do not define the result of the over-run test and thus, the road wear itself. The figures like stud protrusion and stud force did not seem to have a defining effect on wear, and the trends were partly controversial in addition to large dispersion. This supports the main idea behind the over-run test as the objective has been and still is to allow new type of studded tyres that are not limited to strict and rigid limits whenever the road wear can be proved to be sufficiently low. Some effect of stud protrusion, for example, can be detected when comparing different tyres (type-approval data), and it can be said that the traditional dimension-based procedure can still have a place in the type-approval.

The validation of the stone samples today is done by visual inspection and by outside dimensions. A more detailed validation procedure has been discussed including a mechanical testing to prove the uniform properties of the samples in case of inner cracks or other irregularities. Based on the analysis it can, however, be concluded that the samples themselves do not cause primary errors in results as all the sources indicate that the reproducibility within one tester is good enough.

As mentioned, the stud protrusion does not seem to be a major component in the wearing mechanism when inspecting one certain tyre and the wear values within the protrusion variation. What is interesting is that the drive of a vehicle has a clear effect on change of stud protrusion during the test and the final results follow the same trend. A 4WD vehicle has the lowest change of protrusion and the lowest wear on average which may indicate a connection between the protrusion and wear. However, as mentioned, this kind of connection cannot be detected so the wear is affected by other factors. It may be assumed that the testers drive (over the stones) differently and the studs and tyres wear differently when driving with 4WD and 2WD vehicles, which causes the differences on the final results.

Based on the theoretical analysis, only the sources of possible errors may be investigated. Since the definitions in the test method description are loose, it cannot be said how the tester actually conducts the over-run test procedure. However, the theoretical analysis gives hints of possible sources of differences between the testers: the testers probably perform the tests similarly every time but they are not completely aware of the procedures of the other testing companies. As mentioned, the aim to have an as low final result value as possible within the set limits drives the testers toward certain direction what comes to the procedure and methods, but it is uncertain whether all the testers implement the official test method description in the same way. Both the moisture level of the samples (at the beginning) and the variation in the dynamic impact enable significant differences that should be eliminated in the future. The theoretical analysis supports the qualitative analysis which is more or less based on assumptions as inspections were not made in all laboratories.

The angle of incidence or dynamic impact energy probably defines the whole wearing mechanism, and it is something that should be studied more closely in the future. The analysis based on a pure theory with coarse assumptions gave an aggravated result that the method description allows an even 60% difference with one tyre model in the same load index class (see Appendix 2). This can be considered too large compared to reality, but it gives again some guidelines about the loose definitions in the method description. The research work around this matter should be continued.

A possible source of systematic error was also found from the setting of the stones on a track: it was detected that row wear values in one test were sometimes systematically different from each other when comparing tests of one certain testing company. Thus, it seems that the level of the stones may be higher compared to a surrounding track, for example, which causes the first row to wear more than the others.

In addition to the conditions in the testing in its current form, it was confirmed that the stone geometry has a clear and assumed impact on the result of the over-run test. More edges and corners in the stone cause more wear, which would reduce the effect of random variation by increasing the overall wear value. This would also make it possible to detect differences more easily between the testers and conditions. However, larger wear results as such would not remove the fact that differences exist between the testers.

## 4.3 Additional testing

The need for further study was defined to be one of the objectives of this paper as it was known already at the beginning that all the phenomena could not have been inspected on a sufficiently detailed level. A few proposals based on the analysis work done in this thesis are presented below.

**Proof of theoretical calculation**

The theoretical calculation gave large differences in dynamic impact energy. The effect of such variables inspected earlier should be studied in real conditions to confirm the phenomena and to find out the actual scale of the effect. To perform the tests, at least the most extreme combinations presented in Appendix 2 should be tested. This would reveal whether the dynamic impact energy follows the theoretical calculation, and if some dependency were found, there would be a good reason to define these variables on a more detailed level. The procedure regarding the tyre pressure measurement should be elaborated otherwise, too, and that would be a simple thing to do.

**Study about the track profile and setting of the stone frame**

As was seen in Figure 27 on page 59, there seemed to be some systematic differences between individual row wears: the wear in the first row had been the largest for example. With regard to this phenomenon, the conclusion is that something in the stone frame or in the setting of the frame on a track causes these systematic differences that are unwanted. With the help of that, also the profile of a track before the stones was found to be a possible cause for differences between the testers and now, especially between the test tracks. The profile of the test tracks and the real behaviour of a tyre when it crosses the over-run stones could be studied by the help of an instrumental wheel assembled into a vehicle. This instrumental wheel measures and records vertical forces, for example, affecting the wheel in high frequency so that the actual load when the tyre crosses the stones could be inspected. Also other ways to study such phenomenon could be considered.

**Effect of water**

The over-run test stones are kept wet during the driving phase, but the method description defines the watering loosely. According to general understanding, the stones are kept under water as they lay in a frame that is watered constantly. Based on consultation of one of the developers of the over-run test, it could actually be harmful for the test to keep the stones in a puddle so that the over-running tyres might cause pressure shocks on the stones (Unhola, et al., 2016). Therefore, the stones may be cracked or damaged in an undesirable way. The original aim has just been to keep them moist despite external conditions (whether it is raining or not). Moreover, the argued 1.5–3 times higher wear in wet conditions (Unhola, 2015) may actually concern only wear on real pavement material such as asphalt and not the wear in the over-run test on pure stones (Unhola, et al., 2016). Therefore, it would be valuable to conduct a test where the over-run test would be performed on dry, wet and really wet (in a puddle like the situation is now) conditions. Since there is no evidence of the effect of water or moisture in the over-run test, this kind of test procedure would clarify the matter. Another thing relating to watering is whether the rest of the track is watered or not, but the conclusion on this were already made in chapters 3.2.1 and 3.2.3, and the conclusion was that a wet track has an effect on the change of stud protrusion but not necessarily on the result of the test.

**Effect of traction**

It is not certain if all the testers drive over the stones with traction force applied, throttle off, clutch disengaged or gear in neutral. First, this matter should be defined in the method description, but second, it is something that could be studied more closely. The most uniform definition for all vehicle types would be to roll freely over the stones. If traction force is applied, 4WD and 2WD vehicles are set in divergent positions, but the same problem also occurs when pulling up the throttle as engine braking affects differently depending on the drivetrain of a vehicle.

**Over-run test without the over-runs**

When seeking differences between the handling procedures of stones between the testers and unwanted wear on test stones, a justified test procedure would be to conduct the over-run test without the over-runs and just keep the stones under water for that 3h that the over-runs usually take. This would reveal differences between the handling of reference and over-run stones whenever they exist. The procedure should be exactly the same for both stones, but as the weight differences are small and the result is sensitive to errors, this kind of test would clarify the situation although it may seem to be trivial. In addition, if any differences between different types of stones would come up, the comparison between the testers would explain at least a part of the systematic errors.

## 4.4 Improving the over-run test

### 4.4.1 Methods and evaluation

As an objective of the thesis, proposals to develop and improve the over-run test are to be presented. These improvements are introduced in this chapter and they are divided into three separate groups based on the level of easiness of appliance. Changes in the type-approval procedure always cause difficulties or at least changes in the procedures of all involved parties such as manufacturers and testers. The effects of these changes are evaluated in more detailed in the reflection part in the next chapter. The division into three in this chapter is there to separate the changes that are intended to improve transferability by the help of little corrections in the method description, the changes that require a change in the wear limits, for example, and the changes that may even challenge the position of the over-run test in the type-approval procedure.

The presented improvements are based on the statistical analysis that composed a major part of the thesis. In addition to that, several interviews with different parties and their ideas around the over-run testing have been taken into account. The basis for this discussion has been sought from reference material and theory to get confirmation to certain assumptions. However, not everything is validated by the theory or field tests, and also those ideas that are based on opinions or views of people around the testing are introduced: the current test results and evaluation of the test are not available in large scale. The technology of studded tyres alone has developed since the over-run test was first introduced, so the study of the test from those days does not necessarily correspond to the situation today. Whenever the resources allow additional testing, it should be done in order to improve the over-run test to reach a sufficient level in transferability.

The proposals for improvement of the test are quite varying as mentioned, they may be inconsistent with each other and not all suggestions can be applied together. The first section, however, that specifies the simplest changes in order to improve transferability and not to really change the test itself may be considered to be applied all together, but the other proposals are more individual methods and they are presented on a general level only.

### 4.4.2 Group 1: simple to apply

The first group includes the improvements that are the easiest to apply in the over-run test method description. These changes would not cause major difficulties within the testers, either, because the test procedure is only unified and elaborated. In other words, these improvements are something that there is no reason not to define, and thus, they all should be considered as important matters having larger or smaller effect on the transferability of the test. The scale of the effect may not be known and either it should be further studied or one would just need to content oneself with the assumption that new restrictions would improve the test and not harm it in any other way.

**Track**

The setting of the test stones on a track may cause differences in wearing. The stones themselves may be set differently into the frame or the frame may be either on a different level vertically or in an angle compared to the other track surface. The introduction of a uniform mobile steel frame that is filled with the stone samples already at a laboratory has certainly an effect to the harmonisation between the testers. However, the setting of the frame on a track may be an important factor. The method description should define that the stones must be on exactly the same level as the surrounding track surface and no angle between the stone and the track surface is allowed. The track itself is not usually completely horizontal in longitudinal and/or transversal directions so the adjustment of the frame needs to be done according to the track, not according to the horizontal level. In addition, it needs to ascertain that all of the 15 stones are parallel with each other and on the same level. These conditions are most probably fulfilled well already, though. Also the setting of stones into the frame is to be done at the laboratory to ensure high-quality environment for this accurate operation.

In addition to the unevenness at the area of the test stones, the unevenness on a larger scale on a track may cause a vehicle to oscillate so that the load of the vehicle may either lighten or increase when the vehicle is rolling over the stones. This may result in an overall impact on the wear as the load of the vehicle toward the track changes from the original. To make sure that the vehicle goes evenly through the whole track, the surface of the track should be even and planar without any holes or other roughness.

The effect of water on the stones has been discussed, and one argument has been the negative influence of a puddle where the stones are laying during the test. Pressure shocks may cause additional, unwanted and unreal cracking in the test stones, which obviously harms the testing. Another argument concerning the influence of a puddle has been that the tyre may get into hydroplaning or at least the water on the stones lightens the straight load of the tyre to the stones. In other words, the impacts of studs become less impressive. For these reasons, the effect of water should be studied as stated earlier, and the possibilities to avoid these problems should be examined. If both wet and dry stones wear similarly, the definition of watering the stones becomes pointless. This would simplify the procedures of the testers as no watering would need to be arranged on a track. On the other hand, if the watering is discovered to (still) be necessary, the spare water on the stones should be led away so that the stones would not lie in a puddle.

In addition to the watering of the stones, the watering of the complete track was detected to be a difference between the testers. Of course, the weather conditions also define whether a track is wet or dry. However, based on the analysis conducted, no indicatives of the effect of a wet track were found. Stud protrusions have increased more when a track had been dry, though. This is something that could be studied in the future, but it is not the most important factor and the question of watering should be left for the testers as a possibility to control the track temperature that may easily increase above the allowed limit without watering.

**Way of driving**

The way to drive or roll over the stones has already been discussed. Traction force that is applied if a vehicle is driven “normally” over the stones or if a throttle is only pulled up at the stones causes differences in the level of road wear (Gültlinger, et al., 2014). The most uniform way for every vehicle type would be to disengage the clutch or change the gear to neutral so that as low forces as possible come across from the vehicle to the wheels and then to the track. This definition would require nothing but a correction in the method description.

**Vehicle and tyres**

The drive of a vehicle is possibly the most important factor regarding a test vehicle. As was seen earlier, the drive type may cause some 15% difference in the final result of the over-run test between front and four wheel drive vehicles. The matter is well known within the testers and the effect may be taken into account when concluding other type of analyses. However, from the authority's point of view, the fact becomes problematic and it sets the results achieved with different types of vehicles into divergent positions. One justified solution would be to define that an FWD vehicle is to be used in tyre load index classes of less than 100 corresponding to maximum tyre loads of less than 800kg. In these classes, an FWD vehicle would surely always be available on the market, and the justification would also be that most of the vehicles in Finland, for instance, are front driven. An FWD layout also results in the highest wear so that random errors become relatively less significant. On the other hand, in the highest load index class of over 100, the vehicles are already often driven by four wheels. Nonetheless, whatever the decision of drive types will be, a decision should be done in order to unify the testing at least within a certain load index class.

The load of the test vehicle and the load on the left side wheels are loosely defined in the method description. Based on the task force data, even a clear impact of the load to the wear was detected. The first thing to do would be to set tighter limits for the load: an example would be 65–70% of maximum load of the tyre for each tyre. In the load index class 95 which represents a "normal level", the maximum interval for the mass difference is currently some 70kg (one tyre). Furthermore, it could be considered if the load in the test would not be defined with the help of the load index of certain tyre, but fixed limits for each of the four load index classes (LI<90, 90<LI<100, LI>100 and LI=C) would be defined. Based on the theoretical calculation shown in Appendix 2, it would be more likely that they are the tyre size and pressure that make the difference and the load index class itself does not define the wear. A change in the load index may presumably cause a larger difference in wear through the possibility of the variation in loads than the properties of tyres. The fixed load limits would simplify the procedures of the testers as one vehicle with the same load would always fulfil the requirements of one load index class at least. Now the situation with several load indexes and complex definitions in the test method description in addition to the initial shares of load in vehicles may cause issues: an FWD vehicle with an engine in front may have a significant share of the mass in front so that the rear end must be extra loaded, which may, though, cause difficulties within certain tyres with different load indexes. Fixed limits would be a straightforward and predictable way to define the loads.

With regard to the loading of vehicles, the wheel angles were something to be considered as a possible cause for false wearing. At least with the fixed load limits, it would be justified to require the testers to adjust the angles under the testing load. The effect of different wheel angles is something that has not been studied, but it seems natural that wrong angles cause an increase in wear. On the other hand, for this reason it is in the testers' interest to adjust the angles correctly so the phenomenon drives them to act in the best way. A small correction to the method description, however, would be to require the angles to be adjusted under the testing load.

As mentioned, tyre size seems to have an effect on wear at least based on the theoretical calculation. A fixed tyre size for each load index class would be a preferred solution which would again clarify the field of variables. For sure, the defined size would not always be available so that some kind of possibility for an exception should be allowed. However, even a recommended size for each load index class would unify the practices because now the test method description does not take a clear stand on the size of a tyre (other than load index).

With regard to the tyres, also their pressure may have an effect on the result of the test. As has been noted, the test method description does define the pressure, but the temperature where the pressure is to be measured is not defined. Thus, it would be reasonable to require the pressure to be measured and adjusted in the testing temperature. An additional demand could also be to check and correct the pressure if the outside or track temperatures change during the test more than 10°C, for instance. However, as stated in chapter 4.3, the impact of the pressure in addition to the tyre size and load should first be studied on a more detailed level. Nevertheless, at least the definition to measure the pressure at the testing temperature would be easy and justified to set.

**Handling procedure of the stones**

Handling procedures of the testers may cause significant errors in the over-run test result as was presented in chapters 3.2.7 and 3.3.1, for example. First of all, it should be underlined that both the over-run and reference stones must be handled similarly through the whole procedure from stone delivery to the final weighting. In addition, it should be confirmed that a stone deliverer – which must be the same for all the testers – handles the stones in batches so that it can always be confirmed that the stones mined or machined at a different time do not mix together. This would contribute to a correct reference correction.

Storing conditions for the stones are defined in the method description to be warm and dry. This definition should be enough for descent testing as long as the over-run and reference stones are again stored in the same conditions. A preferred way to ensure uniform handling of the stones would be to divide the stones into sets that include both the over-run and reference stones for one complete over-run test right away when the stones are delivered to a tester. It should also be possible to confirm that the stones in one set come from the same batch already at the stone deliverer.

To reduce the effect of reference correction and, thus, also the errors that may exist there, the stones should be as dry as possible at the beginning of the test. It was described in chapter 3.3.1 that the change in the mass of a test stone due to moisture or evaporation becomes negligible if the stone is dry enough. One way to reduce the reference correction – and thus, the possible error caused by the reference correction – would be to dry the stones at the beginning before any other action. To find out and define the proper drying conditions and time, additional testing would be needed, but according to the earlier moisture analysis in chapter 3.3.1, a few weeks of drying in around 100°C would be satisfactory. By this, the problem with too large reference corrections would disappear and the possibility of an error would be minimised. After this first drying phase, the normal procedures could be started.

The effect of time from the cooling section to the weighting may affect the result because air humidity may increase the moisture in the stones if they lie on a table, for example, for long. A possibility to false reference correction, for instance, exists. The impact is presumably small, but the matter should be defined in the description. The conditions –

temperature and humidity – in a laboratory should also be defined to some extent, and the way to do the measurement must be similar within all the testers. It would be justified to define the over-run and reference stones to be weighted in certain order (within certain time frame) so that the reference correction would not become larger than what it should be, and at least the procedure would always be the same.

### 4.4.3 Group 2: need for redefinition of the road wear limit value

The second group includes improvements that require that the limit for road wear value received as a result of the over-run test is redefined due to significant change of wearing level. The idea, though, is to retain the basis of the over-run test and not to develop a new test. The suggestions here are based on the general overviews that have come up during the research of the over-run test in this thesis.

The first problem in the over-run test is the minimal mass loss of the stones even when some 3 hours are spent in constant driving. Such a low change in a mass lets no room for any unwanted errors, and that is why the over-run test in its current form gives varying results depending on the tester even though the test method description is extensive. A simple way to increase the wear in the test has already been introduced: smaller knobs sawed on the stone. As was seen in chapter 3.2.5, smaller knobs with narrower grooves resulted in higher wear. In this case, the level of the more or less random errors caused by moisture in the stones would relationally decrease, but it still seems uncertain whether the dispersion or confidence limits with these kinds of stones would be improved or not. Additional testing for the new type of stones would be needed in order to ensure the real benefit. Changing the restriction limits for the wear is difficult in any case, so it really needs to be considered whether to end up in a situation that requires setting new limits.

At the same time, also other type of sawed matrices on top of the stones could be studied as possibilities for the future test stone. Based on the theory, transversal grooves sawed on top of the stones might increase wearing more from the current situation if the grooves were narrow and densely sawed. This would reduce the corners of knobs where some unwanted random cracks may happen. Transversal grooves would be reasonable based on the deduction that the studs move longitudinally and not transversally in a contact with a track in the over-run test. In normal driving conditions on the rutted roads, transversal forces may also be significant, though.

Another stone related change would be to find out a new material for the test samples. It seems that granite is quite tough material and the wearing happens more or less by cracks. Homogenous and a bit softer material could be found from ceramics or the material could be a concrete-type mixture. However, a major problem with a new material would be to confirm its suitability for the over-run test and also validate its use as representative of real pavement material. At least the connection between the real road wear and the wear of this new material should be studied. Thus, it may seem that this kind of changes are too heavy to implement even in the long run as all of the parties around the over-run test have invested in it in its current form. There is a strong belief that the over-run test can be made more reliable and especially transferable in its current form with relevant corrections and continuous work.

### 4.4.4 Group 3: aim in the future

The third group includes only one main idea for the testing of the road wear of studded tyres in the future: a laboratory test. The best practice to measure road wear as far as it is known is the inner drum test bench at the Karlsruhe Institute of Technology (KIT) presented in chapter 2.5. The bench for road wear testing only in certain conditions would not have to be as complex as the bench at KIT is. However, the investment for this kind of high-end laboratory device would become too large for each of the testers, and the most feasible way to implement this would be to acquire only one laboratory in Finland, for example. Nevertheless, the laboratory test would enable not only exactly the same method for each test but also the use of real pavement materials in the testing. Increasing the "number of over-runs" would be possible in order to get as much wear as is needed for sufficiently good tolerance of random errors. The idea seems still raw and it is not something that has been planned to be implemented in the following years, but it should be kept in mind.

## *4.5 Evaluation of the test and improvements*

This chapter primarily aims to answer the research questions that were defined in the beginning in chapter 1.2. As an overall evaluation of the success to find solutions for the problems in the over-run test, it can be stated that several factors causing differences in the test could be found and some strong beliefs of certain phenomena could be confirmed. Of course, as the data was scattered and the limits for the thesis are defined, it was not possible to solve or clarify everything. Nevertheless, after implementing the suggested improvements, the level of repeatability and transferability is to be inspected again, and the effect of these changes must be found out in reality.

Some of the factors that cause systematic errors in the over-run test were recognised whereas some of them were evaluated to have some kind of effect, but the impact of them could not be defined more detailed. It is still uncertain if the proposed improvements would decrease the variation between the testers to a sufficient level until new test rounds are done.

It seems that random errors have a place in the over-run test as they have in the field testing in general. In addition, there are multiple variables affecting especially the tyre testing: the rubber mixture and studding, as examples. However, the suggested improvements would also reduce the effect of random errors as the test method description in a new form would not allow as much variation within one tester, and it would elaborate certain phases of the procedure which presumably have also an effect on random errors. Furthermore, the detected fact is that the results of one tester have been on a good level what comes to repeatability. Thus, it seems that whenever the results of each of the testers are on the same level, the test fulfils the requirements concerning the overall reliability of the test.

The most extensive list of improvements was categorised into the simple to apply -group in chapter 4.4.2 and those points are only additions and corrections to the current test method description. Therefore, it would be presumable that a great improvement in transferability could be achieved if those improvements were implemented. As mentioned earlier, the level of variation in the test results between the testers should be studied and evaluated after the implementation of these changes. Then, it may be possible to find out whether these improvements are sufficient. For now, there is a strong belief that with the help of these developments, the over-run test would be greatly improved and its position concerning the type-approval procedures would be strengthened.

The effect of the proposed improvements on the transferability of the over-run test should be evaluated by another test round by all the testers. If it seems that these changes in the method are not sufficient, it may be asked if all the necessary things are measured in the test: is there something that causes differences in the results that is not measured and inspected and thus, that cannot be detected in the current data? Not all, but many of the measured things have been analysed in this thesis and many of the possible conclusions from the current available data have already been considered elsewhere, too. The lack of feasible measures may be a reason for the unawareness of the causes for errors, so measuring new variables and phenomena could be one way to find solutions to this matter. In addition, the future aim should be kept in mind and the possibility to implement major changes in the testing of studded tyres seen in chapters 4.4.3 and 4.4.4 should be considered.

As a conclusion, the implementation of the presented suggestions would improve the test as such because the differences between the testers would become narrower. However, the improvements would need extra effort from the testers, but it would be more than justified in terms of quality. In addition, no other way to measure road wear – that would be easy to apply and affordable in the near future – has been detected. Returning to the traditional dimension-based method would not be a foreseeable solution. Therefore, it seems that the only way forward now is to implement the suggested and other similar slight changes in the method. Based on the analysis, it seems probable that the transferability would improve.

## 4.6 Effects in the market

The question of the use of studded tyres is not only an issue in Finland but also in other countries as described in chapter 2.3. The over-run test itself has also a significant position abroad as Sweden recognises the approvals granted in Finland and also Norway has taken them into account. In addition, whenever the strengths and the value of the over-run test can be seen over the world, the test may improve its visibility and popularity among other countries where the use of studded tyres is extensive, such as in Russia and countries in North America. Thus, the development of the over-run test cannot be done only based on the needs and the situation in Finland. Nordic co-operation would be natural including also the large market of Russia. All parties – the authorities, testers and manufacturers – would be satisfied if the legislation were uniform in these countries. If common and reasonable legislation could be created, the possibility for other countries to follow this method to control road wear and air quality, among other things, would be higher.

## 4.7 Future outlook

One of the general objectives of the road wear testing and legislation concerning studded tyres overall is to control road wear without significant losses in safety. This aim must always be kept in mind in order to achieve major objectives in the society regarding the question of studded tyres. To achieve all the main objectives – safety, cost efficiency and healthy traffic – the responsibility should not fall only on the tyre industry, but also means like restrictions or compensations for the users of certain kinds of tyres or even vehicles should be taken into use. It is also the pavement industry that can majorly affect the situation around the conversation of road wear and studded tyres.

Concerning the over-run test, the reliability should reach a sufficiently good level, and the question here seems actually to be transferability. One does not consider the test dependable if different testers get different results with the same tyres. By improving the test to a great level, it would be justified for the authority to tighten the limits for road wear according to a defined plan. The natural development of this kind of performance test relating health, among other things, is to lower the limits over a time. The trend is seen for example with vehicles' exhaust emissions. A reasonable test would ensure this development as false or accidental approvals would not get through.

Even if the over-run test were qualified as a reliable and transferable test that also indicates the road wear in reality in traffic, all new types of testing methods should constantly be kept in mind in order to still emphasise the testing of studded tyres against road wear. The existing laboratory methods could provide a more valuable and affordable way to do measurements with less human effort in the future. An issue with the over-run test in the coming years may also be that the wearing effect of studded tyres will decrease which means that the random errors represent an even larger proportion of the final result.

The thesis proposals for the improvement of the over-run test are considered important. In addition, the task force works hardly to find out own conclusions. The deductions of this thesis have partly been made together with the task force, and in the future, too, the ideas from all parties must be considered. Trafi as an authority managing the over-run tests and approvals has certainly a word to say when deciding and defining the future.

In addition to the concrete improvements to the test method, a study is to be done in the future to improve the test even further. It would be reasonable to study the wearing mechanism of road and the test stones in order to better understand the factors that affect them. Partly based on that, new materials for the test sample may be considered to increase the mass loss in the test still to reduce the relational effect of random errors that always exists anyway.

# 5 Conclusion

The aim of the thesis was to study the over-run test of studded tyres and the differences in the results of the different testing companies, recognised experts. During the past few years when the over-run test has been part of the type-approval procedures to show the road wear of tyres to be approved, a lot of research and development has been conducted mostly by the testers themselves. Now, the supervisory authority in Finland, Finnish Transport Safety Agency (Trafi), was willing to engage in the development process by having a thesis made. In addition to Finland, the situation regarding the over-run test also concerns Sweden and Norway, for instance, as they recognise or have recognised the approvals granted in Finland by the over-run test.

From the authority's point of view, the current situation seems problematic as different testing companies have different results from the same test. The testers had done developing work in co-operation with each other and Trafi, and they had conducted multiple tests to study the effects of different factors affecting the over-run test. The working group of the testers, the task force, provided their data for this thesis, and the main part of the paper was to conduct a statistical analysis and with the help of that, find the factors that may cause systematic errors or differences between the testers and tests. Thus, the data used in this paper as one of the most important references, is produced by a third party – the earlier described task force – and neither Trafi nor the author have produced any of the data that is based on real field tests. In addition to the differences in the provided data, the differences or errors that may be possible according to the over-run test method description were evaluated. So, the statistical analysis composed a major part of the thesis, but in addition to that, the theoretical (both quantitative and qualitative) analysis was there to support the deductions.

The range of recognised factors that may cause differences in the test results was wide and varying. Also some factors that were evaluated to cause differences based on interviews and feelings among the interest groups were speculated. Nevertheless, the most important conclusions based on the research are shortly described here. First, the reference stones that are there in the test to even out the changes in moisture level in the test stones were evaluated to possibly cause differences depending on the origin of the stones and their handling during the over-run test procedure. Moisture, as small as it is, may cause some dozens of percent error in the result if the procedure is done falsely for one reason or another. Therefore, the suggestion that both the over-run and reference stones go through the whole procedure from the mining to the final weighting together as sets including all 20 stones that are needed in one over-run test, was made in the thesis.

The second main conclusion of the analysis was that it is presumable that the setting of the 15 over-run stones or the setting of the stone frame on a test track causes differences in row wears and thus, final results of the test. It was shown that the row wears of different tests by the same tester differed systematically from each other: that is to say that for example the first row's wear had been the highest, which indicates that the stones may be on a higher level than the surrounding track. This vertical difference may presumably be small and not detected by visual inspection without special equipment. The task force started to proceed with this and they are to conduct a test round to inspect this phenomenon.

Third, a theoretical examination and a much simplifies calculation based on different tyre pressures, tyre sizes and vehicle loads were done to support the noticed effect of such variables in the statistical analysis. Pressure is affected by temperature whose effect was seen in the data. In addition to pressure, also the behaviour of rubber depending on temperature may emphasise the phenomena. The presumable effect of load was also seen in the statistical analysis. Based on the observations, a suggestion was made to tighten the limits regarding these factors in the over-run test. On the other hand, based on the results of this analysis, the task force agreed to carry on the research concerning these variables and they also added specific tests for these factors in their test program.

In addition to the observations that were more or less new, the existing knowledge about affecting factors was confirmed. First, the results from the tests driven with modified test stones with smaller knobs were analysed, and the presumed conclusion that the smaller knobs cause a larger mass loss in the stones in the test was detected. However, due to the fact that only few tests conducted, the effect of smaller knobs to the deviation could not be confirmed. Additional tests with modified stones were decided to be done by the recognised experts in order to increase wear to reduce the effect of random errors. The second phenomenon that was already known – the effect of the drive of a vehicle – was confirmed. A 4WD vehicle was noticed to have the smallest wear and an FWD vehicle the highest. Based on this result, a proposal that same type of vehicle with regard to the drive should be used within certain load index class: it is justified to require smaller tyres to be tested with an FWD vehicle whereas a 4WD vehicle was suggested to be used in higher load index classes.

The most important results of the thesis were partly new observations and partly confirmation to the existing understanding. Nevertheless, both types of findings were widely implemented to the testing program of the recognised experts, which can already be considered valuable. In addition, there are good reasons to believe that the suggested improvements reduce the differences in the test procedures of all testers and thus, the results produced by all the testers. After all, after implementing the suggested improvements, another test round between all the testers is to be done in order to confirm the presumed effects. Transferability after the described developments should improve and even reach a sufficiently good level considering the type-approval procedures. It must be noted that field testing always includes variation due to numerous variables, and tyre testing does not make an exemption. Until now, the sources of variation have not been recognised completely, but with the help of patient development work, the over-run test will be able to fulfil the requirements for an official standard, too. Thus, it will be more probable for the over-run test to be implemented or recognised outside of Finland, too, and by this, the market of studded tyres may get closer to the general objective of common legislation in countries where studded tyres are in use – especially the Nordic countries and Russia that make a natural market area.

# Bibliography


**Alkio, Risto. 2016.** Nastarenkaiden yliajokoe. *[E-mail] message to Janne Syvänen.* 20 April 2016.

**ATCF. 2016.** The Automobile and Touring Club of Finland (Autoliitto). *Tietoja ja vinkkejä ulkomaan matkailuun.* [Online] 2016. [Cited: 7 May 2016.] http://www.autoliitto.fi/matkailu/vinkit/automatkalle/tietoa_ja_vinkkeja_ulkomaan_matk/.

**Chen, Renjie, et al. 2011.** Coarse particles and mortality in three Chinese cities: The China Air Pollution and Health Effect Study (CAPES). *Science of the Total Environment.* 2011. Vol. 409, pp. 4934-4938. doi:10.1016/j.scitotenv.2011.08.058.

**City of Helsinki. 2013.** Kitkarenkaiden käytöllä parempaa ilmanlaatua. Helsinki : Public Works Department, 2013.

**City of Helsinki. 2016.** Katuojen hoitoluokitus. [Online] 2016. [Cited: 16 May 2016.] http://www.hel.fi/www/helsinki/fi/kartat-ja-liikenne/kadut-ja-liikennesuunnittelu/katujen-kunnossapito/hoitoluokitus.

**Elvik, Rune. 1999.** The effects on accidents of studded tires and laws banning their use: a meta-analysis of evaluation studies. *Accident Analysis and Prevention.* 1999. Vol. 31, pp. 125-134. doi:10.1016/S0001-4575(98)00054-2.

**Elvik, Rune. 2015.** Can electronic stability control replace studded tyres? *Accident Analysis and Prevention.* 2015. Vol. 85, pp. 170-176. doi:10.1016/j.aap.2015.09.012.

**Elvik, Rune and Kaminska, Joanna. 2011.** Effects on accidents of reduced use of studded t yres in Norwegian cities. Oslo : Institute of Transport Economics, 2011. TØI report 1145/2011.

**Elvik, Rune, et al. 2013.** Effects on accidents of changes in the use of studded tyres in major cities in Norway: A long-term investigation. *Accident Analysis and Prevention.* 2013. Vol. 54, pp. 15-25. doi:10.1016/j.aap.2013.02.004.

**ETRMA. 2016.** Correlation analysis between Over-Run test and VTI PM (Particulate Matter) Study. *ETRMA Report.* Brussels : European Tyre and Rubber Manufacturers' Association, 2016.

**Finnish legislation.** *Decree on the Use of Vehicles on the Road 1257/1992.* Adopted in Helsinki on 4 December 1992.

**Finnish legislation.** *Decree of Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003.* Adopted in Helsinki 20 May 2003.

**Finnish legislation.** *Act on the Finnish Transport Safety Agency 863/2009.* Adopted in Helsinki 13 November 2009.

**Finnish National Road Administration. 1993.** Kokemuksia Japanin nastattomasta talviliikenteestä. Helsinki : Liikenteen palvelukeskus, 1993. ISSN 0788-3722, ISBN 951-47-8117-1, TIEL 3200191.

**FMI. 2016.** The Finnish Meteorological Institute's open data. [Online] 2016. [Cited: 26 May 2016.] https://en.ilmatieteenlaitos.fi/open-data.

**FTA. 2016.** The Finnish Transport Agency. *Teiden talvihoito.* [Online] 2016. [Cited: 16 May 2016.] http://www.liikennevirasto.fi/tieverkko/kunnossapito/talvihoito#.VulHFVK53hm.

**Gertler, Alan , et al. 2005.** A case study of the impact of winter road sand/salt and street sweeping on road dust re-entrainment. *Atmospheric Environment.* 2005. Vol. 40, pp. 5976–5985. doi:10.1016/j.atmosenv.2005.12.047.

**Grönfors, Timo. 1975.** Tutkimus nastarenkaista ja nastan pistovoimasta. *Master's thesis.* Espoo : Helsinki University of Technology, 1975. 237pp.

**Gültlinger, Johannes, et al. 2014.** Investigations of Road Wear Caused by Studded Tires. *Tire Science and Technology.* 2014. Vol. 42, 1, pp. 2-15.

**Gustafsson, Mats, et al. 2008.** Factors influencing PM10 emissions from road pavement wear. *Atmospheric Environment.* 2008. Vol. 43, pp. 4699–4702. doi:10.1016/j.atmosenv.2008.04.028.

**Gustafsson, Mats, et al. 2008b.** Properties and toxicological effects of particles from the interaction between tyres, road pavement and winter traction material. *Science of the Total Environment.* 2008. Vol. 393, pp. 226-240. doi:10.1016/j.scitotenv.2007.12.030.

**Gustafsson, Mats, et al. 2009.** Nanopartiklar från slitage av däck och vägbana. Linköping : Swedish National Road and Transport Research Institute (VTI), 2009. ISSN 0347-6030. VTI Rapport 660.

**Gustafsson, Mats and Eriksson, Olle. 2015.** Emission of inhalable particles from studded tyre wear of road pavements. Linköping : Swedish National Road and Transport Research Institute (VTI), 2015. VTI rapport 867A, Reg. No., VTI: 2013/0662.

**Gustafsson, Mats and Eriksson, Olle. 2015b.** ETRMA Studded tyre tests at VTI 2015. Linköping : Swedish National Road and Transport Research Institute (VTI), 2015.

**Halonen, Jaana I., et al. 2009.** Particulate Air Pollution and Acute Cardiorespiratory Hospital Admissions and Mortality Among the Elderly. *Epidemology.* 2009. Vol. 20, pp. 143-153. ISSN: 1044-3983/09/2001-0143, doi:10.1097/EDE.0b013e31818c7237.

**Heikkinen, Harri. 2012.** Nastarenkaiden vaikutus päällysteiden kulumiseen taajamanopeuksissa. *Licenciate Thesis.* Espoo : Aalto University, School of Engineering, 2012. 119pp.

**Jacobson, Torbjörn and Wågberg, Lars-Göran. 2007.** Utveckling och uppgradering av prognosmodell för beläggningsslitage från dubbade däck samt en kunskapsöversikt över inverkande faktorer. Linköping : Swedish National Road and Transport Research Institute (VTI), 2007. VTI notat 07-2007. Version 3.2.03.

**Junghard, Ola. 1992.** Estimating the traffic safety effect of studded tires. *Accident Analysis & Prevention.* 1992. Vol. 24, 4, pp. 357-361. doi:10.1016/0001-4575(92)90048-N.

**Kelkka, Marko, et al. 2003.** Hiljaiset päällysteet - Tuotevaatimukset ja mittarit. *Publications in Highway Engineering.* Espoo : Helsinki University of Technology, 2003. TKK-TIE-A55.

**Kim, Ki-Hyun, Kabir, Ehsanul and Kabir, Shamin. 2015.** A review on the human health impact of airborne particulate matter. *Environment International.* 2015. Vol. 74, pp. 136-143. doi:10.1016/j.envint.2014.10.005.

**KIT. 2014.** Karlsruhe Institute of Technology (KIT). *Investigations of road wear caused by studded tires (presentation slides).* Helsinki : EDEN expert meeting, 2014.

**KIT. 2016.** Karlsruhe Institute of Technology (KIT). *Testing Facilities, Institute of Vehicle System Technology (FAST).* [Online] 2016. [Cited: 25 February 2016.] https://www.fast.kit.edu/download/DownloadsFahrzeugtechnik/140519-Testing_facilities_FAST_english.pdf.

**Kupiainen, Kaarle, Tervahattu, Heikki and Räisänen, Mika. 2003.** Experimental studies about the impact of traction sand on urban road dust composition. *The Science of the Total Environment.* 2003. Vol. 308, 1–3. doi:10.1016/S0048-9697(02)00674-5.

**Kupiainen, Kaarle and Tervahattu, Heikki. 2004.** The Effect of Traction Sanding on Urban Suspended Particles in Finland. *Environmental Monitoring and Assessment.* 2004. Vol. 93, pp. 287-300.

**Kupiainen, Kaarle, J. and Pirjola, Liisa. 2011.** Vehicle non-exhaust emissions from the tyre – road interface – effect of stud properties, traction sanding and resuspension. *Atmospheric Environment.* 2011. Vol. 45, pp. 4141-4146. doi:10.1016/j.atmosenv.2011.05.027.

**Kupiainen, Kaarle, et al. 2013.** Talvirenkaiden pölypäästöt ja eri katupölylähteiden osuudet kadunvarrella kerätyissä hiukkasnäytteissä. Helsinki : Helsingin seudun ympäristöpalvelut -kuntayhtymä, 2013.

**Lahti, Tapio. 2003.** *Ympäristömelun arviointi ja torjunta.* Helsinki : Edita, 2003. ISBN 952-11-1353-7.

**Lampinen, Anssi. 1993.** *Kestopäällysteiden urautuminen.* Espoo : VTT, 1993. ISBN 951-38-4129-4.

**Lanki, Timo. 2013.** Katupölyn vaikutukset terveyteen. Terveyden ja hyvinvoinnin laitos, 2013.

**Lindén, Unto. 1979.** Raskaan ajoneuvon nastarenkaan nastan liike dynaamisen tilanteen tiekosketuksessa. *Master's thesis.* Espoo : Helsinki University of Technology, 1979. 136pp.

**Määttä, Anne, et al. 2012.** Helsingin kaupungin meluselvitys. Helsinki : City of Helsinki, Environment Centre, 2012. ISSN 1235-9718, ISBN 978-952-272-265-2.

**Mäkinen, Tapani. 1994.** Nastarenkaiden vaikutus matkoihin ja kuljettajien riskinottoon. Helsinki : Finnish National Road Administration, 1994. TIEL 4000054.

**Malmivuo, Mikko. 2012.** Nastarenkaiden vähentämisen liikenneturvallisuusvaikutukset. Helsinki : Ministry of Transport and Communications, 2012. ISSN 1795-4045, ISBN 978-952-243-288-9.

**Malmivuo, Mikko and Luoma, Juha. 2016.** Rengastyypin vaikutukset lumi- ja jääpolanteen liukkauteen ja kulumiseen. Espoo : VTT Technical Research Centre of Finland Ltd, 2016. VTT TECHNOLOGY 244. ISBN 978-951-38-8392-8.

**Nordström, Olle. 2004.** Nya och begagnade vinterdäcks isfriktion. Linköping : Swedish National Road and Transport Research Institute (VTI), 2004. VTI meddelande 966.

**Rajamäki, Riikka. 2014.** SUPPEA ANALYYSI: Yliajokokeen tulosten vaihtelu. Finnish Transport Safety Agency, 2014.

**Rantonen, Marko, Tuononen, Ari and Sainio, Panu. 2012.** Measuring stud and rubber friction on ice under laboratory conditions. *International Journal of Vehicle Systems Modelling and Testing (IJVSMT).* 2012. Vol. 7, 2, pp. 194-207. doi:10.1504/IJVSMT.2012.048447.

**Repo, Harri. 2006.** Betonitiet jäivät Suomessa kokeiluksi. *Tekniikka ja Talous.* [Online] 2006. [Cited: 17 May 2016.] http://www.tekniikkatalous.fi/tekniikka/rakennus/2006-08-17/Betonitiet-j%C3%A4iv%C3%A4t-Suomessa-kokeiluksi-3252630.html.

**Roine, Matti. 1999.** Accidents risks of car drivers in wintertime traffic. Espoo : VTT Technical Research Center of Finland, 1999. ISSN 1235-0621.

**Rumar, Kåre , et al. 1976.** Driver Reaction to a Technical Safety Measure — Studded Tires. *Human Factors: The Journal of the Human Factors and Ergonomics Society.* 1976. Vol. 18, 5, pp. 443-454. doi: 10.1177/001872087601800503.

**Sandberg, Ulf and Ejsmont, Jerzy A. 2002.** *Tyre/road noise reference book.* Kisa : Informex, 2002. ISBN 91-631-2610-9.

**Savenius, Jarkko. 2002.** Nastarenkaiden käytön vaikutukset. *Master's thesis.* Espoo : Helsinki University of Technology, 2002. 99pp.

**Scheibe, Robert R. 2002.** An Overview of Studded and Studless Tire Traction and Safety. Washington : Washington State Department of Transportation, 2002. WA-RD 551.1.

**SFS-EN 12697-16. 2004.** Bituminous mixtures. Test methods for hot mix asphalt. Part 16: Abrasion by studded tyres. Helsinki : Finnish Standard Association, 2004. p. 30+1.

**Stansfeld , Stephen A. and Matheson, Mark P. 2003.** Noise pollution: non-auditory effects on health. *British Medical Bulletin.* 2003. Vol. 68, pp. 243–257. DOI: 10.1093/bmb/ldg033.

**Strandroth, Johan, et al. 2012.** The effects of studded tires on fatal crashes with passenger cars and the benefits of electronic stability control (ESC) in Swedish winter driving. *Accident Analysis and Prevention.* 2012. Vol. 45, pp. 50-60. doi:10.1016/j.aap.2011.11.005.

**Suokonautio-Hynninen, Susanna. 2016.** The Automobile and Touring Club of Finland (Autoliitto). Talvirengaslainsäädäntö. *[E-mail] message to Janne Syvänen.* 16 May 2016.

**Task force. 2015.** "Task force data": numerical data set of the comparison over-run tests conducted in 2015. *Provided to Janne Syvänen as confidential information by the working group of the over-run test, task force.* 2015.

**Tervahattu, Heikki, Kupiainen, Kaarle and Räisänen, Mika. 2002.** Katupölyn tutkimusprojekti - Katupölyn muodostuminen ja koostumus koeolosuhteissa. Mobile2 vuosiraportti 2001. Helsinki : Nordic Envicon Oy, University of Helsinki, 2002.

**Trafi. 2013.** Over-run Test. *Memorandum.* 2013.

**Trafi. 2014.** Yliajokoemenetelmäkuvauksen tarkentava liite. [Online] 2014. [Cited: 17 February 2016.] http://www.trafi.fi/filebank/a/1430729756/bef45563e869170671ce4bafc5552d22/17480-Yliajokoemenetelman_vaatimukset.pdf. TRAFI/7664/05.03.44/2014.

**Trafi. 2014b.** "Comparison test data": numerical data set of the comparison over-run tests conducted in 2013–2014. *Provided to Janne Syvänen by Finnish Transport Safety Agency (Trafi).* 2014.

**Trafi. 2016.** Tieliikenne - Luvat ja hyväksynnät. [Online] 2016. [Cited: 5 February 2016.] http://www.trafi.fi/tieliikenne/luvat_ja_hyvaksynnat.

**Trafi. 2016b.** "Type-approval data": Type-Approval Certificates of studded tyres granted in 2015–2016 through the over-run test procedure. *Provided to Janne Syvänen by Finnish Transport Safety Agency (Trafi).* 2016.

**Tuononen, Ari and Sainio, Panu. 2013.** Optimaalinen nasta-kitkarengassuhde jäisellä tiellä - NASTAVIRTA loppuraportti. Aalto University, 2013.

**Tuononen, Ari and Sainio, Panu. 2014.** Optimal proportion of studded tyres in traffic flow to prevent polishing of an icy road. *Accident Analysis and Prevention.* 2014. Vol. 65, pp. 53-62. doi:10.1016/j.aap.2013.12.009.

**Unhola, Timo. 1995.** Rengasnastan ulkoneman ja pistovoiman vaikutus tien kulumiseen ja pitoon. VTT Yhdyskuntatekniikka, 1995. Tutkimusraportti 304, VTT/YKI, LM, 3/9//95-YKI54.

**Unhola, Timo. 1997.** Nastarenkaiden tiekulumavertailu. VTT Yhdyskuntatekniikka, 1997. Tutkimusraportti 407, VTT/YKI, LM; Dno. 1/9/97-YKI54,.

**Unhola, Timo. 2004.** Nastarenkaiden kuluttavuus. Ajoneuvotekijöiden vaikutus. Yliajokoe 2004. Helsinki : Ministry of Transport and Communications, 2004. ISSN 1457-7488 (printed), 1795-4045 (electronic).

**Unhola, Timo. 2015.** Yliajokoe. Selvitys kokeen kehitysvaiheista ja tyyppi-hyväksyntärajojen määräytymisperusteista. Finnish Transport Safety Agency Trafi, 2015. ISBN 978-952-311-100-4, ISSN 2342-0294.

**Unhola, Timo, Solla, Anu and Vesala, Hannu. 2004.** Nastarenkaan kuluttavuus yliajokokeessa ja imurimenetelmällä. Helsinki : Ministry of Transport and Communications, 2004. ISSN 1457-7488, ISBN 951-723-878-9.

**Unhola, Timo and Alkio, Risto. 2016.** Nastarenkaiden yliajokoe. *[E-mail] message to Janne Syvänen.* 20 April 2016.

**VTI. 2016.** The Swedish National Road and Transport Research Institute (VTI). *VTI Road Simulator.* [Online] 2016. [Cited: 25 February 2016.] http://www.vti.se/en/research-areas/environment/air-pollution-and-quality/vti-road-simulator/.

**VTT. 1986.** Nastan painon vaikutus tien päällysteen kulumiseen. Espoo: Valtion teknillinen tutkimuskeskus, Tie- ja liikennelaboratorio. 1986. Tutkimusselostus 583.

**VTT. 1987.** Nastan muodon ja painon vaikutus tien päällysteen kulumiseen. Espoo : Valtion teknillinen tutkimuskeskus, Tie- ja liikennelaboratorio, 1987. Tutkimusselostus 624.

**VTT. 1989.** Nastan painon vaikutus tien kulumiseen. Espoo : Valtion teknillinen tutkimuskeskus, Tie- ja liikennelaboratorio, 1989. Tutkimusselostus 745.

**VTT. 2014.** Puhdistustoimenpiteiden sekä kuivatus- ja jäähdytysajan vaikutus kivinäytteiden massaan. Espoo : VTT Expert Services Oy, 2014. VTT-S-01208-14.

**White, Tomas D., et al. 2002.** Contributions of Pavement Structural Layers to Rutting of Hot Mix Asphalt Pavements. Washington, D.C. : National Academy Press, 2002. ISSN 0077-5614, ISBN 0-309-06721-9.

**Zubeck, Hannele , et al. 2004.** Socio-economic Effects of Studded Tire Use in Alaska. Anchorage : University of Alaska Anchorage, 2004.

# Appendices

Appendix 1. The over-run test method description. 5 pages.
Appendix 2. Simplified calculation of the dynamic impact of a stud. 3 pages.
Appendix 3. Example of calculation of the reference correction. 1 page.

## Appendix 1. The over-run test method description

**Over-run test method description,**
**Appendix with more detail**
Version 1.0
TRAFI/7664/05/03/1944/2014

| Date of issue: | Date valid: | Valid until: |
|---|---|---|
| 03/04/2014 | 12/05/2014 | Until further notice |

Statutory basis:
Paragraph 3 of Section 3 and Paragraph 2 of Section 7 of the Decree of the Ministry of Transport and Communications on Studs on Vehicle Tyres 408/2003 (latest amendment 466/2009)

Revision details:
First version 1.0

# Over-run test method description, Appendix with more detail

| **Procedure** | **Method/limit value/quantity** |
|---|---|

| **Testing:** | | |
|---|---|---|
| | Length of the test track | Sufficient, so that the vehicle accelerations do not exceed the maximum allowed value. |
| | Shape of the test track | The test stones are overrun in both directions. |
| | | The inclination of the test track directs excess test stone wetting water away from the test location. |
| | Surface of the test track | Major rutting is not allowed. |
| | Wetting of the test stones | 100-150 l/h |
| | Test stone wetting water | Tap water |
| | Vehicle speed | Passenger car 100 km/h, +/- 2 km/h |
| | | light-weight truck (C tyre) 80 km/h, +/- 2 km/h |
| | | The required speed must be achieved 50 m before reaching the test stones. |
| | Vehicle accelerations | Below 2 $m/s^2$ |
| | Number of test stone overruns | 400 crossings by tyres. |
| | Reference stones | Kept underwater in a container in the vicinity of the test track for the duration of one test. |
| | | Each set of reference stones may only be used to correct the results of one test. |

| **The placement of test stones in the frame:** | | |
|---|---|---|
| | Frame base | Must be protected from the elements when test runs are not being performed. |
| | | Must be carefully cleaned before setting the test stones. |
| | The setting of test stones into the frame | 3 rows, with 5 test stones in each row. |
| | Material between the test stones | Rubber |
| | Thickness of the material between the test stones | 3 mm +/- 0.5 mm |
| | Overlapping of the test stones | The rows of test stones are overlapped/staggered at distances of 3 mm +/- 0.5 mm relative to the crossing direction. |
| | Material between the test stone rows | The material in contact with the test stones is rubber. There is a rigid support between the rubbers (e.g. metal) with which the test stones are secured into the frame. |
| | Thickness of the material between the rows of test stones | 5 mm +/- 2 mm |
| | Tightening of the test stones into the frame | Stones are tightened so that they remain in place during the test. |
| | Dimensional accuracy of the test stones | The height difference between the test stones used in the same test must be 0.5 mm or less. |

| **Test conditions:** | | |
|---|---|---|
| | Air temperature | +2… +20 |
| | | Temperature is measured in the shade prior to beginning the test. |
| | Road temperature | +2… +25 |
| | | Temperature is measured prior to beginning the test, at the half-way point of the test and after the test, on the track at a location where there is no spray from test stone wetting water. |
| | Tyre temperature | The temperatures of the test tyres are measured. |
| | | Measurement performed from the side of the test tyre at a distance of 5 cm from the rim edge. The same, even spot is used during each measurement. The measurement is performed prior to the beginning of the test, during the test (while switching drivers) and after the test. |

| **Test tyre:** | | |
|---|---|---|
| | Age of the test tyres | The test is carried out using new, unused tyres that have been manufactured at least two weeks prior to the beginning of the test. |
| | | Studding must have been carried out at least 48 hours prior to the beginning of the test. The technical service does not need to monitor the studding process. |
| | Pressure, cold tyre | under 600kg, 2.3 bar +/- 0.1 bar |
| | | 600 to 800kg, 2.5 bar +/- 0.1 bar |
| | | over 800kg, 2.7 bar +/- 0.1 bar |
| | | C, 3.5 bar +/- 0.1 bar |
| | Even quality of the studding | Tyres cannot be accepted for testing if one or more of several conditions are fulfilled:<br>1) The protrusion of an individual stud on the test tyres is over +/- 30 % of the average stud protrusion of the test tyres.<br>2) The average stud protrusion of the test tyres is over +/- 10 % of the target stud protrusion intended by the tyre manufacturer/studder. |
| | | With target stud protrusions of under 0.5 mm, individual stud protrusion may<br>differ from the target value by a maximum of +/- 0.1 mm. |
| | | If the studded tyre manufacturer/studder does not report the target stud protrusion, the test tyre will not be accepted for testing. |
| | | 20 consecutive studs are measured from both test tyres over the entire tread, beginning from a random point; in any case, this should be done using the same studs on the same tyre. |
| | Stud protrusion changes during over-run test procedure | The average stud protrusion of the test tyres after the test may not have changed by over +/- 25 % from the average stud protrusion of the test tyres measured prior to the over-run test. Average stud protrusion of the test tyres: ((Average stud protrusion of the test tyre on front axle + average stud protrusion of the test tyre on rear axle) / 2) |
| | | 20 consecutive studs are measured from both test tyres over the entire tread, beginning from a random point; in any case, this should be done using the same studs on the same tyre. |

| **Test vehicle:** | | |
|---|---|---|
| | Condition | The vehicle must be in good condition |
| | Traction method | Free |
| | Transmission | Free |
| | Loading | For the entire vehicle, 65-75 % of the sum of the maximum loads of the test tyres |
| | | For an individual tyre, 60-80 % of the maximum of the load index |
| | | Less than 5 % difference between the left-hand and right-hand tyre masses |
| | | Less than 5 % difference between the front and rear axle masses |
| | | The masses are measured prior to the test |
| | Tyres not run over the test stones | Must be the same as the test tyres |
| | Rims | STRO or ETRTO |

| **Measuring equipment:** | | |
|---|---|---|
| | Test stone scales | Accuracy +/- 0.001g |
| | Oven | Convection oven |
| | Oven size | There must be room for a minimum of seven plates of test and reference stones, with the different sets of stones on their own plates |
| | Cooling device | Desiccator / vacuum chamber / cabinet drier |
| | Outdoor thermometer | Accuracy +/- 1 $^0$C |
| | Oven thermometer | Accuracy +/- 1 $^0$C |
| | Road thermometer | Accuracy +/- 1 $^0$C |
| | Tyre thermometer | Accuracy +/- 1 $^0$C |
| | Tyre pressure meter | Accuracy +/- 0.1 bar |
| | Vehicle scales | Accuracy +/- 5 kg |
| | Accelerometer | Accuracy +/- 0.1 $m/s^2$ |
| | Stud protrusion gauge | Accuracy +/- 0.01 mm |
| | | The geometry of the measuring device's base must fulfil the specifications in Appendix 1. |

| **Test and reference stones:** | | |
|---|---|---|
| | Work drawing of the test and reference stones | The test and reference stones must meet the specifications in Appendix 2. |
| | Number of test stones to be run over | 15 pcs. |
| | | Used for a single test only. |
| | Number of reference stones | 5 pcs. |
| | | Used for a single test only. |
| | | The reference stones may not be used as run-over stones after the test. |
| | Test and reference stone material | Grey Kuru granite. |

| **Processing of the test and reference stones:** | | |
|---|---|---|
| | Cleaning | Under tap water with a light application of a dishwashing brush. Use pressurised air to remove excess water. |
| | Cleaning water | Tap water |
| | Dry in a convection oven | 3 days ± 2 h |
| | | The test and reference stones are placed into the oven before and after the over-run test, always in the same places and with the same orientation. |
| | Cooling | 120 min +/- 5 min |
| | | Air humidity 10 % or less |
| | | The test and reference stones are placed into the cooler in such a way that they do not touch each other. |
| | | The test and reference stones are placed into the cooler before and after the over-run test, always in the same places and with the same orientation. |
| | Long-term storage | The test and reference stones are stored in a dry, warm space. |
| | Transportation of test and reference stones | Must be transported to the test location in a container/frame so that they are not subjected to external forces (impacts and abrasion). |

| **Stud force measurement during the over-run test:** | | |
|---|---|---|
| | Stud force measurement | Performed before the over-run test. |
| | Procedure for measuring the stud force of a passenger car tyre stud | The stud force is measured in accordance with Paragraph 2 with the exclusion of items a), c) and d), and Paragraphs 3 and 4 of Section 5 of the Stud Decree 408/2003 (latest amendment 466/2009). |
| | Procedure for measuring the stud force of a light-weight truck tyre and a truck tyre | The stud force is measured in accordance with Paragraph 2 with the exclusion of items a) and c), and Paragraph 3 of Section 6 of the Stud Decree 408/2003 (latest amendment 466/2009). Paragraph 3 refers to the incorrect Section; the correct reference should be to Section 5. |

| **Stud protrusion measurement during the over-run test:** | | |
|---|---|---|
| | Stud protrusion measurement | The measurement is performed prior to the stud force measurement and after the over-run test |
| | Number of measurements | 20 consecutive studs are measured from both test tyres over the entire tread, beginning from a random point; in any case, this should be done using the same studs on the same tyre. |
| | The pressure force of the measuring device against the tyre | 15-20 N |
| | Measurement result | Average stud protrusion of the test tyres. Average stud protrusion of the test tyres: ((Average stud protrusion of the test tyre on front axle + average stud protrusion of the test tyre on rear axle) / 2). |

| **Results:** | | |
|---|---|---|
| | Result | The average wearing value (g) of the rows at a precision of two decimal places. |
| | Taking the reference stones into consideration | Average mass change that is used to correct individually each test stones weighing result |
| | Allowed reference correction | If the mass loss percentage of even a single reference stone is greater than 0.025 % compared to the original mass, the reference correction cannot be used. However, the test tyre can be approved, if the wear without reference correction is less than the defined limit value in accordance with the limit values section. Mass loss percentage: ((Reference stone mass measured prior to the test - reference stone mass measured after the test) / reference stone mass measured prior to the test) * 100. |
| | Confidence interval | 95 % confidence that the error calculated for the row-specific wear results is<br>less than 15 %. |
| | Approval | If the measurement result is at least 10 % below the limit value. |
| | | If the results of two tests are below the limit value. |
| | Retesting | Required if the result is less than 10 % below the limit value. |

| **Limit values for the wear the tyre causes:** | | |
|---|---|---|
| | Load rating class under 600 kg | 0.9 g |
| | Load rating class 600-800 kg | 1.1 g |
| | Load rating class over 800 kg | 1.4 g |
| | Load rating class C | 1.8 g |

# Appendix 2. Simplified calculation of the dynamic impact of a stud

Two different tyre sizes have been taken into account, both with maximum and minimum load and at both cooling and warming temperatures. Only one load index class is inspected. All these cases are possible according to the type-approval procedure in the same tyre class. This calculation is much simplified, and it is not clear how the road wear is affected by the calculated impact energy, for example. Possible factors such as the shape of the stud, its attachment on the tyre, rubber hardness, driving style et cetera are not included here. The theoretical approach to the matter highlight the differences between the set-ups, and the numerical values presented may not represent reality, but they must be inspected as guidelines. Therefore, this examination gives only ideas regarding the effect of these factors and shows that the method description enables this kind of differences. Absolute values for the impact energy, for instance, have been replaced by relative values showing only the relation to the average in the result table.

As the calculation is much simplifies, certain assumptions have been made:

- the pressure in a tyre carries the entire load, not a side of a tyre
- the pressure in a tyre stays the same (the volume of a tyre stays the same when the tyre is flattened vertically but at the same time, spread horizontally at the sides of the tyre not making the tyre wider at the footprint, though)
- the load is evenly distributed at the footprint
- the footprint of a tyre is rectangular
- the load increases only the length and not the width of a footprint
- the pins of the studs are on the same level as the rubber surface of the tyre (in reality, a stud has a protrusion that, on the other hand, is only some 1mm)
- the profile of the outer shape of the tyre is either flat (at footprint) or completely circular (elsewhere)

It is assumed that it is an isochoric change in a tyre and air inside is ideal gas so the relation of pressure and temperature is the following:

$$\frac{p'_1}{T_1} = \frac{p'_2}{T_2} \qquad (1)$$

$$\begin{aligned} &p'_1 = p_1 + p_{nor}\ [Pa] \\ &p'_2 = p_2 + p_{nor}\ [Pa] \\ &p_1 = initial\ gauge\ pressure\ at \\ &\qquad a\ temperature\ T_1\ [Pa] \\ &p_2 = gauge\ pressure\ at \\ &\qquad a\ temperature\ T_2\ [Pa] \\ &p_{nor} = atmospheirc\ pressure\ [Pa] \\ &T_1 = temperature\ in\ the\ measuring\ [K] \\ &T_2 = temperature\ during\ the\ test\ [K] \end{aligned}$$

$$\frac{p_1 + p_{nor}}{T_1} = \frac{p_2 + p_{nor}}{T_2} \qquad (2)$$

Now the (gauge) pressure in a tyre during a test at a temperature $T_2$ is:

$$p_2 = \frac{(p_1 + p_{nor}) * T_2}{T_1} - p_{nor} \qquad (3)$$

The relation between a load for an inspected tyre, tyre pressure and footprint area is:

$$G = p_2 * A \qquad \left| \begin{array}{l} G = m * g = gravitational\ force\ [N] \\ A = l * w = footprint\ area\ [m^2] \end{array} \right. \tag{4}$$

$$m * g = p_2 * l * w \qquad \left| \begin{array}{l} m = mass\ for\ an\ inspected\ tyre\ [\mathrm{kg}] \\ g = gravitational\ coefficient\ \left[\frac{m}{s^2}\right] \\ l = lenght\ of\ a\ footprint\ [m] \\ w = width\ of\ a\ footprint/tyre\ [m] \end{array} \right. \tag{5}$$

Now the length of a footprint can be defined:

$$l = \frac{m * g}{p_2 * w} \tag{6}$$

The angle of incidence of a stud toward a track follows the equation:

$$\sin \alpha = \frac{l/2}{r} \qquad \left| \begin{array}{l} \alpha = angle\ of\ incidence\ [°] \\ r = nominal\ radius\ of\ a\ tyre\ [m] \end{array} \right. \tag{7}$$

When combining the equations (6) and (7), the angle of incidence can be calculated:

$$\sin \alpha = \frac{m * g}{2 * r * p_2 * w} \tag{8}$$

The connection between a nominal radius and a dynamic rolling radius of a tyre is:

$$r_{dyn} = r * \cos \alpha \qquad \left| \ r_{dyn} = dynamic\ rolling\ radius\ of\ a\ tyre\ [m] \right. \tag{9}$$

The radial velocity of a stud can be defined:

$$v_r = \frac{r}{r_{dyn}} * v_t \qquad \left| \begin{array}{l} v_r = radial\ velocity\ of\ a\ stud\ [m/s] \\ v_t = velocity\ of\ a\ stud\ at\ a\ track \\ \qquad contact\ [m/s] \\ \qquad (= 100km/h = 27.78m/s)) \end{array} \right. \tag{10}$$

By means of the law of cosine, the change in velocity of a stud can be defined when it hits a track:

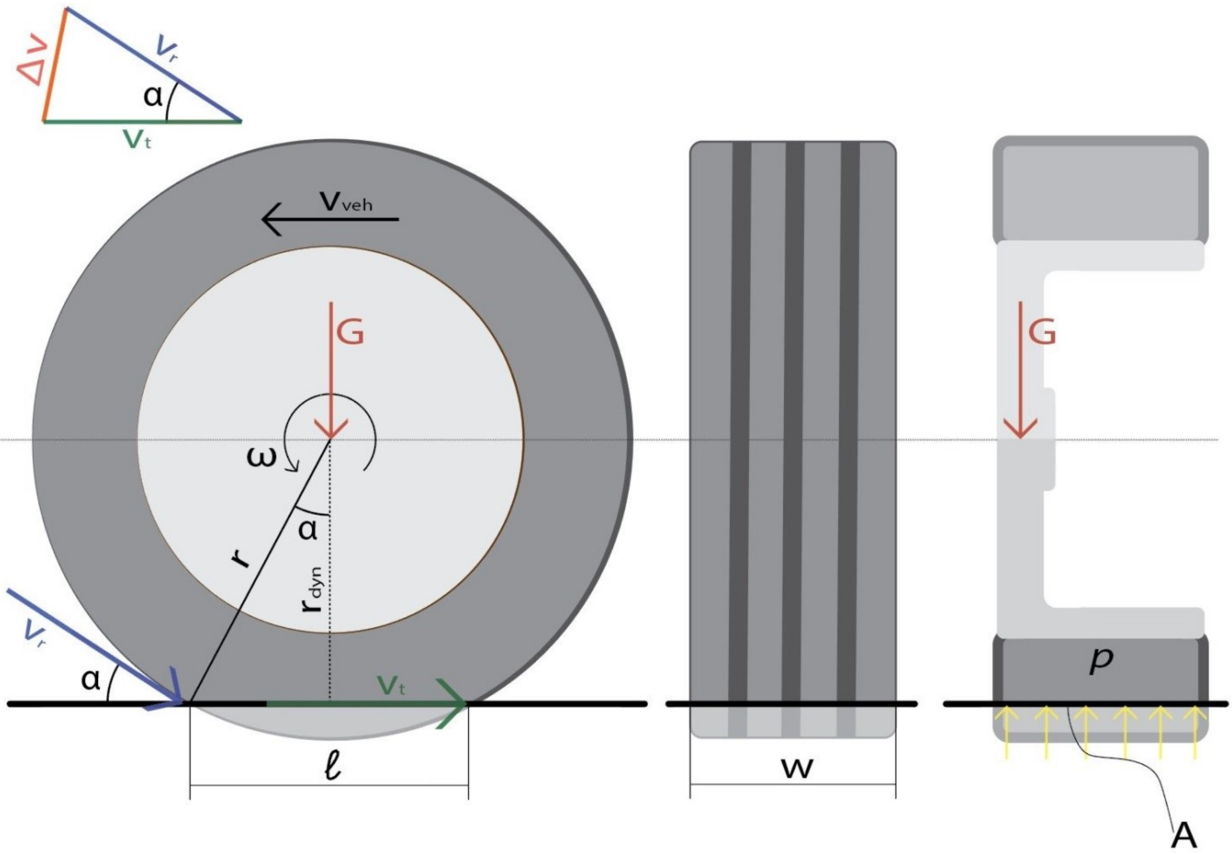
$$\Delta v = \sqrt{{v_r}^2 + {v_t}^2 - 2 * v_r * v_t * \cos \alpha} \tag{11}$$

With the help of the change in velocity, the change in kinetic energy of a stud can be defined:

$$\Delta E_k = \frac{1}{2} * m_{stud} * \Delta v^2 \qquad \left| \begin{array}{l} m_{stud} = mass\ of\ a\ stud\ [kg] \\ \qquad (= 1g = 0.001kg) \end{array} \right. \tag{12}$$

In addition, the vertical momentum of a stud impact can be calculated:

$$I = m_{stud} * v_r * \sin\alpha \tag{13}$$




**Relational factors (1.00 representing an average) for an angle of incidence, impact energy and momentum in different scenarios. Load index used as an example is 95 corresponding to 690kg.**

| Tyre size | Temperature change | Load | Angle of incidence | Impact energy | Momentum |
|---|---|---|---|---|---|
| *Reference (average)* | | | *1.00* | *1.00* | *1.00* |
| 195/65R15 | 10 → 20°C | Max load | 1.11 | 1.24 | 1.11 |
| 195/65R15 | 10 → 20°C | Min load | 0.92 | 0.82 | 0.92 |
| 195/65R15 | 20 → 10°C | Max load | **1.23** | **1.52** | **1.23** |
| 195/65R15 | 20 → 10°C | Min load | 1.02 | 1.01 | 1.02 |
| 225/45R17 | 10 → 20°C | Max load | 0.97 | 0.92 | 0.97 |
| 225/45R17 | 10 → 20°C | Min load | **0.80** | **0.62** | **0.80** |
| 225/45R17 | 20 → 10°C | Max load | 1.07 | 1.23 | 1.07 |
| 225/45R17 | 20 → 10°C | Min load | 0.88 | 0.75 | 0.88 |
| *Max difference* | | | *35%* | *59%* | *35%* |

# Appendix 3. Example of calculation of the reference correction

**Average masses of the over-run stones (measured)**

| | Before the over-runs [g] $m_{start}$ | | | After the over-runs [g] $m_{end}$ | | | Road wear without the reference correction [g] $\Delta m_{mea} = m_{start} - m_{end}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Row 1 | Row 2 | Row 3 | Row 1 | Row 2 | Row 3 | Row 1 | Row 2 | Row 3 |
| Stone 1 | 321,213 | 322,104 | 317,624 | 321,061 | 321,919 | 317,456 | 0,152 | 0,185 | 0,168 |
| Stone 2 | 322,521 | 318,951 | 320,153 | 322,318 | 318,752 | 319,964 | 0,203 | 0,199 | 0,189 |
| Stone 3 | 319,965 | 319,979 | 321,302 | 319,670 | 319,723 | 321,051 | 0,295 | 0,256 | 0,251 |
| Stone 4 | 320,006 | 320,531 | 319,639 | 319,743 | 320,268 | 319,358 | 0,263 | 0,263 | 0,281 |
| Stone 5 | 320,509 | 320,101 | 322,512 | 320,308 | 319,862 | 322,301 | 0,201 | 0,239 | 0,211 |
| Sum | 1604,214 | 1601,666 | 1601,230 | 1603,1 | 1600,524 | 1600,130 | 1,114 | 1,142 | 1,100 |
| **Average** | | | **1602,370** | | | **1601,25** | | | **1,119** |

**Average masses of the reference stones**

| | Before the test [g] $m_{r\_start}$ | After the test [g] $m_{r\_end}$ | Change [g] $\Delta m_{ref} = m_{r\_start} - m_{r\_end}$ | [%] $c_{ref} = \Delta m_{ref} / m_{r\_start}$ |
|---|---|---|---|---|
| Stone 1 | 322,635 | 322,56 | 0,075 | 0,0232 % |
| Stone 2 | 321,315 | 321,244 | 0,071 | 0,0221 % |
| Stone 3 | 319,657 | 319,593 | 0,064 | 0,0200 % |
| Stone 4 | 321,811 | 321,744 | 0,067 | 0,0208 % |
| Stone 5 | 322,984 | 322,913 | 0,071 | 0,0220 % |
| **Average (used as a reference correction value for measured wears)** | | | | **0,0216 %** |

| | Average masses of the over-run stones after the test including the reference correction $m_{cor} = m_{mea}*(100-c_{ref})\%$ | | | Reference corrected wears $\Delta m_{final} = m_{start} - m_{cor}$ | | |
|---|---|---|---|---|---|---|
| | Row 1 | Row 2 | Row 3 | Row 1 | Row 2 | Row 3 |
| Stone 1 | 321,143 | 322,034 | 317,555 | 0,082 | 0,115 | 0,099 |
| Stone 2 | 322,451 | 318,882 | 320,084 | 0,133 | 0,130 | 0,120 |
| Stone 3 | 319,896 | 319,910 | 321,232 | 0,226 | 0,187 | 0,181 |
| Stone 4 | 319,937 | 320,462 | 319,570 | 0,194 | 0,194 | 0,212 |
| Stone 5 | 320,440 | 320,032 | 322,442 | 0,132 | 0,170 | 0,141 |
| Sum | 1603,867 | 1601,319 | 1600,884 | 0,767 | 0,795 | 0,754 |
| **Average** | | | **1602,023** | **Final result:** | | **0,772** |